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SOIL POLLEN ANALYSIS

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Summary

Acidic soils (pH below 5·5) may contain a great deal of pollen through the profile, and the floristic composition of this pollen may vary greatly in samples from successively greater depths.

Various attempts have been made in the past to interpret pollen diagrams from soils, but they have usually broken down through the application of methods of interpretation which are only applicable to properly stratified materials such as peats or lake sediments. Once it is appreciated that downwash of pollen through the soil confers on each species a depth distribution pattern characteristic of its history on the site, broad conclusions about the vegetative history of a site can frequently be drawn.

The preservation of pollen depends on the biological activity of the soil, which is closely correlated with pH. Soils which have only been decalcified recently will have a short pollen record, perhaps only a few centuries, but intrinsically base-poor parent material may permit preservation for several millennia.

Introduction

Sooner or later in any discussion about soil development or soil processes a question is raised about the previous history, of vegetation or treatment, of the particular profiles under discussion. Sometimes old documents can provide some information but at best these go back only a few centuries. More often the question has to be left unanswered.

Recent work has shown that in acid soils pollen may be preserved for very long periods and that from the distribution of the various pollen types in the soil a general picture of past vegetational change—often indicating change of treatment—may be built up. Interest in past history has largely been the concern of the ecologist hitherto, but pedologists are now making their own pertinent inquiries in this subject, and it is to answer some of their questions that this paper has been written. Pedological details are omitted here, but full correlations of the past vegetation with the soil types of the sites mentioned will be published elsewhere.

Historical

It has been known for a long time (Beijerinck, 1933) that heath soils may contain pollen and that much of it may date back for thousands of years. On such pollen data Beijerinck (1934) propounded a theory that bleached sand and Ortstein were formed independently under different climatic conditions, and this misinterpretation was carried to fantastic lengths by Jonas and his co-workers in Germany (e.g. Benrath and Jonas, 1937). The theories evolved so contradicted all other work on soil formation that attempts were made to discredit the foundation upon which the theories had been built, namely the pollen analyses. So we have seen Tüxen and Diemont (1936) arguing that the pollen stratification in podzols can have no significance because of downwash through root channels, &c. We now know that this effect can be observed, super-

imposed on the stratification, in certain cases; but it cannot and does not explain the stratification itself. A similar criticism was levelled by Dewers (1936), whilst admitting that pollen analysis could make limited contributions. The matter was brought into perspective by Engmann (1938) who advocated the greatest care in the application of pollen analysis to problems of soil formation. Nevertheless, the analyses made by Jonas hold a great deal of interest if one looks at the facts and not the interpretation, and it is unfortunate that research workers have shied away from this line of inquiry as a result of this past controversy. Even in recent literature, e.g. Scamoni (1950), one still finds the view that the pollen analysis of mineral soils is best avoided; indeed all the sands are shunned for fear of quicksands.

It is perhaps a pity that the early work was done on blown sands, since the history of the sand accumulation was then of more interest than the history of the vegetation. Had the initial inquiries been carried out on soils derived *in situ* the misunderstandings might have been avoided. This is not to minimize the difficulties which many workers see in the application of such analyses. For instance a searching and factual criticism of the pollen analysis of sands was presented by Selle (1940) to whose work it is worth while referring in more detail. He found that the diagrams obtained from the bleached sand of heath podzols, though following broadly the pattern obtained from adjacent bog analyses, differed seriously in detail, leading to conclusions which were at variance with accepted theories. For instance, in one of his analyses (Lohheide) he finds a lime maximum early in the beech period, which seems nonsense. But anomalies such as this are the result of interpreting these diagrams as though they were peat profiles. Selle goes to some lengths to discredit analysis of this material by quoting evidence (Mothes, Arnoldt, and Redmann, 1937) to show that pollen can wash down into sands. He does not realize that from this fact springs the value of the method; neither does he realize that the work he quotes is hardly relevant to the problems, since pollen does not wash down as individual grains but apparently in aggregates bound together by organic matter. Hence the rate of washdown is on a totally different scale from what experimental results in the laboratory may indicate—a scale which varies widely from soil to soil. Looked at as distribution curves whose modes indicate relative age, Selle's apparently senseless diagrams take on a more reasonable appearance. The lime peak in the Lohheide series referred to above does not coincide with the beech peak, which occurs 12 cm. higher in the profile. The peaks of the pine curves, which are all near the surface, are seen by Selle as the result of the inability of pine pollen to wash down owing to its great size and its shape, and he implies that some of this may even be of Boreal Age. This is a failure to realize how recent species tend to be over-represented in the surface of a soil. Moreover, had these data been presented as simple percentages and not as percentages of the tree pollen total, they would have fallen better into perspective. The surface layers clearly represent open country, and the tree pollen rain is likely to be small; pine itself will be the main tree species contributing pollen (cf. Jonassen, 1950).

Analyses from sites of this sort must not be interpreted as though they were bog sites for another reason. The vegetation growing on a bog is seldom taken into account in interpreting pollen analyses, since the significant pollen, that of trees, is transported. In soil pollen analyses, however, the vegetation on the site contributes the bulk of the pollen and it is not to be expected that it will give a picture of the regional pollen rain. When Selle condemns the value of one of his analyses because he finds a high Ericaceae count in the Atlantic period, he may, in fact, be observing the truth but he interpreted the evidence as though it reflected the general flora of the area instead of the flora of the site itself. In fact, one of the features of his analyses which strikes me is the occurrence of deep-lying ericoid pollen; it may hold a clue to the origin of the present ecological status of this region. That lime pollen is differentially preserved is very probably true, yet the fact that percentages of lime exceed those found in bogs is not in itself a good argument against soil analyses, again because the bog is collecting a general pollen spectrum, and the soil an essentially local one. Acid soils may not have carried the same forest type as the better soils and this can only be discovered from the soils themselves. The regional pollen rain reflects the influence of all habitats and therefore cannot serve as the criterion for any one.

An additional effect which may make its appearance in hardpan profiles is the accumulation of the older pollen types just above the pan, as has been observed in some Yorkshire soils (Dimbleby, 1957). It is in cases such as this that frequencies as well as percentages prove so useful in interpretation.

I have discussed Selle's work at some length because it is the most comprehensive and recent treatment of this subject. It serves to emphasize that analyses of this sort must be approached with a mind unconditioned to the reading of normal pollen diagrams. It also draws attention usefully to some of the drawbacks of this method, particularly those arising from differential preservation.

Erdtman (1943) resuscitated the pollen analysis of mineral soils as a useful method, though the significance of his work was generally overlooked. More recently several workers have sparred rather tentatively with pollen analysis of the mineral soil. Though Scamoni confined his attention almost entirely to the raw humus layers, a number of his profiles covered the upper layers of the mineral soil and one even went down as far as the B horizon. Similarly, Rodenwald and Hauff (1957) treated the mineral soil with circumspection, though one profile yielded interesting data from these layers, whilst Mraz and Pacltova (1956) examined a complex profile down to the subsoil, finding pollen at all levels. There have in the past been serious misinterpretations of pollen profiles even from raw humus layers, but in general these are accepted as being more akin to stratified peats in not being subject to mixing processes nor having pollen from an earlier era mixed with the more recent.

A mere mention of the use of pollen analysis to check site history in relation to the present soil was given by Scheys, Dudal, and Baeyens

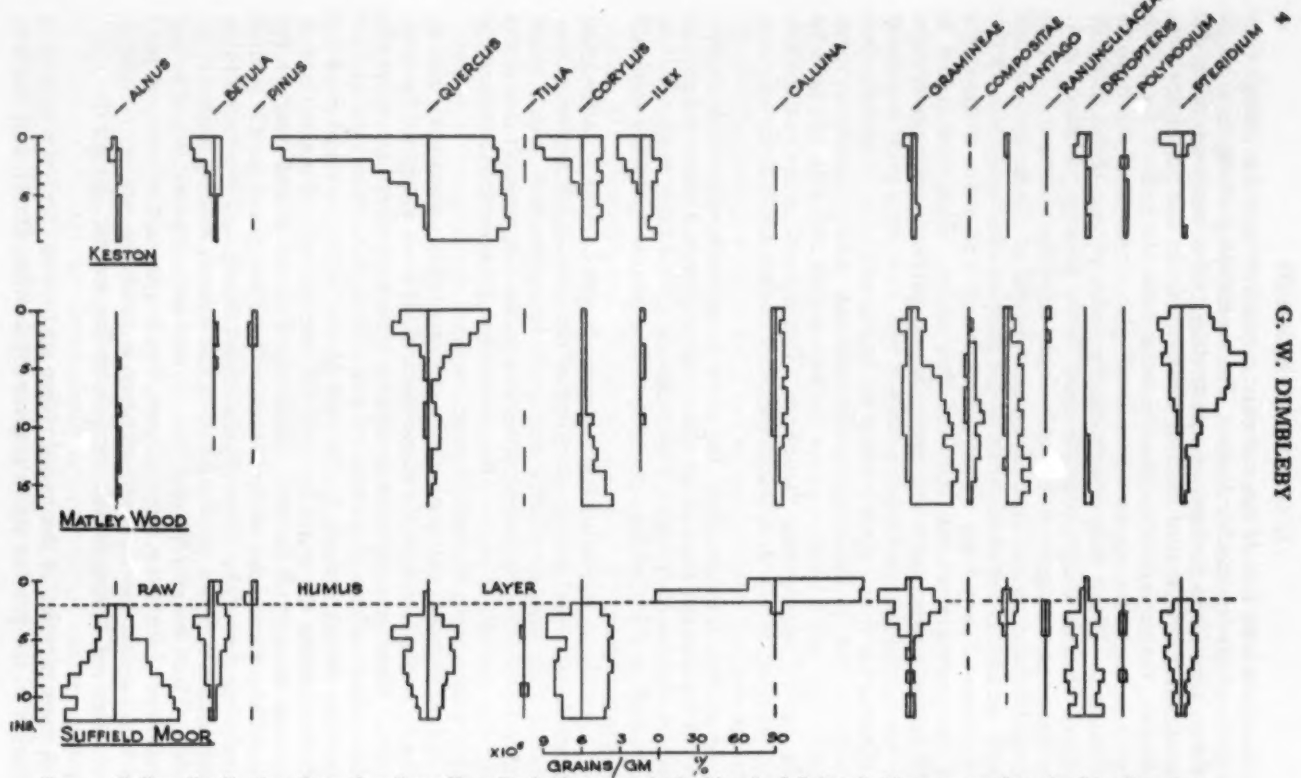

FIG. 1. Pollen distribution through soil profiles. Each histogram is double, the left-hand side representing absolute frequency (grains/gm. soil) and the right-hand side percentages (of total pollen + fern spores).

(1954), but no details were given of the technique or results. More recently the pollen analysis of mineral soils has been extended to a considerable diversity of investigations. The vegetative history of degraded soils in Britain has been widely investigated by this method (Dimbleby, 1955, 1958; Dimbleby and Gill, 1955), and Godwin (1958) has described a pollen record going back as far as the Late-glacial period. In Switzerland Welten (1958) has used it to determine the date of colonization of high alpine slopes by vegetation and to establish vegetation sequences. He dated his earliest phases at about 5000 B.C. It is interesting that, in the environments he studied, pollen was present in soils of much higher pH than it would be in Britain. More recently still Munaut (1959) has used the method to demonstrate changes in forest and other vegetation types from prehistoric times onwards in the podzolized loess soils of Belgium. It is significant that none of these workers finds any contradiction between their results and interpretations and the accepted principles of ecology and pedology, as was the case when the first analyses of pollen in mineral soil were made.

Method

Better techniques for the treatment of soil samples have been adopted since the last account, and details of the present method based on details given by Faegri and Iversen (1950) are given as an Appendix. Briefly, the soil is dried, powdered, and sieved, and a sample of known weight (usually 1 g.) treated with caustic soda, acetolysis mixture and hydrofluoric acid, to destroy the organic matter and the mineral matter. Usually this is completely effective, but occasionally even this drastic treatment leaves behind much besides pollen. For instance, in the surface humus layer many unmodified plant remains survive the treatment, whilst in clays, especially if kaolinitic, there may be a considerable mineral residue withstanding the action of hydrofluoric acid. Even in such cases a pollen count is usually possible though more difficult.

Interpretation

It has been found that both percentages and frequencies are necessary for a complete interpretation of pollen analyses; therefore both these dimensions are normally included in the pollen diagrams, the percentages being based on the total of pollen and fern spores, and not on the tree pollen total, for reasons given earlier (Dimbleby, 1957). In an undisturbed soil the total frequency is normally greatest at the surface and decreases with depth.

The interpretation of the figures obtained in terms of the plant communities at any one stage is only possible at a general level, but this suffices for most purposes. This point was discussed in an earlier paper (Dimbleby, 1957) but is so frequently a source of difficulty to those who are asked to accept the conclusions without knowing the background that the point is returned to here.

First of all, the analyses presented here are complete analyses; they

do not cover only the tree pollen as do most analyses. This point is important because the predominance of non-tree pollen is a certain indication of the absence of trees. There are many plants which occur in forests, e.g. grasses and Ericaceae, but their flowering under a canopy is reduced to such an extent that they represent only a small proportion of the total pollen. Even a shrub like hazel, which can be a prodigious pollen producer, is less so under a canopy; consequently very high hazel values are suggestive of hazel scrub rather than underwood.

Where one finds a mixture of considerable proportions of both non-tree species and tree species, the most likely explanation seems to be that there is a mosaic of vegetation types. The non-tree species must be in the open, or they would not be flowering to a sufficient extent, and the trees must be near enough to influence the pollen rain. A point which particularly bothers many people is the extent to which pollen can be carried over large distances. Distant transport undoubtedly takes place, but on the evidence it seems unlikely that, on sites covered with a vegetation of flowering plants, it normally makes a very great contribution to the total pollen rain. From a recent series of papers honouring the late Alfred Dengler it is apparent that there may be great variability in the effect of distant transport according to circumstances, especially climatic, at the time of pollen production. Persson (1955) gives a number of diagrams which illustrate this point clearly. However, the small extent to which present-day surface samples are influenced by nearby vegetation types, even in open country, gives confidence that no great error is introduced by distant transport, at any rate on total pollen counts. This was confirmed by Scamoni who compared the pollen spectra of the uppermost layers of raw humus with the composition of the forest canopy. With the exception of pine—a species seldom met in my investigations—the effect of outside pollen rarely reaches 3 per cent. of the tree pollen. Recently a number of workers (e.g. Sarvas, 1956) have reached the conclusion that long-distance pollen transport has only a slight significance in pollination. Dengler (1955) demonstrated the marked filtering effect of forest, particularly young plantations, and one would expect this to apply also to dense scrubby woodland. In open country, however, as Jonassen (1950) showed, the effect of distant pollen transport is rather greater; he was, of course, basing his percentages on the tree pollen. Even so, Sarvas (1955) showed that the sea may provide a real barrier to transport between land masses through the elimination of convectional air currents.

Apart from error from outside contamination, another frequent objection to the use of pollen analyses in soils is the differential breakdown of different types. This point was discussed at some length before, and it is one which it is very difficult to assess quantitatively. It is well known that certain species are highly resistant to breakdown, whilst others are rarely if ever found (e.g. poplar). Interpretation can only be based on what is there and usually the presence of only two or three well-preserved types is enough to characterize the vegetation. For example in Table 1, showing four actual spectra, the italicized figures are adequate to give

a picture of the vegetation type, bearing in mind what was said above about conditions necessary for flowering.

TABLE I

	Oak	*Pine*	*Hazel*	*Heather*	*Grasses*	*Plantain*	*Ferns*
1	0·4	14·3	0·7	*62·4*	*16·5*	0·7	0·5
2	0·4	..	10·0	..	*40·8*	*29·0*	10·5
3	*50·2*	..	*11·9*	0·2	1·5	1·0	*14·0*
4	2·9	..	3·3	0·4	*46·2*	2·9	7·7

(No other species reaching 6 per cent.)

The other groups add details without materially altering the overall ecological picture.

It is fortunate that the ecological dominants of the main vegetation types, forest, scrub, heath, and grassland, are among those whose pollen is well preserved; there is therefore little likelihood of the vegetation type being wrongly deduced through lack of representation of the dominant. This may not be so true of the marshy and swampy sites, but these are not dealt with in this paper. Perhaps mention should be made of the special circumstances of an artificial community—the Neolithic cornfield. The early cereals were self-pollinated (Iversen, 1949) and did not release their pollen freely. Consequently, they were greatly under-represented and the community could only be recognized by the associated species.

In his investigation of Dutch barrow floors, Waterbolk (1954) came to the conclusion that there was no selective preservation of species, though some types were much more liable to damage than others. However, he was dealing only with buried surfaces and not with pollen which has penetrated into the soil and so been subject to prolonged microbiological action. Under these circumstances only the more resistant types are to be found at the lowest levels and it is in such cases that frequency serves to show that these are not relics of spectra occurring higher up the profile, but actually represent an increased frequency of these groups in the deeper layers.

It is sometimes held as an objection to soil pollen analysis that any pollen stratification will be destroyed by soil-mixing animals such as earthworms. This, of course, would be true; Ray (1959) has demonstrated by experiment that the larger earthworms quickly carry pollen through any part of the soil in which they are working. The existence of a pollen stratification, therefore, is probably in itself good evidence that no such mixing is taking place; in general the acidity which is necessary for the preservation of pollen is sufficient to exclude the soil-mixing species of worm.

It is obvious that there must always be some error in the results of this method due to the various causes which have been discussed above. These, however, are usually small, and since the changes in pollen spectra are often quite dramatic, and in any case interpretation is only in general terms, it is unlikely that such errors will lead to serious misrepresentation of the ecological sequence.

Examples

1. *Keston Camp*

This analysis is of the buried humus-iron podzol beneath an Iron Age rampart. Changes through the historical period are therefore eliminated and the pollen record gives the history prior to the construction of the rampart.

The high pollen frequencies at the surface, falling progressively with depth, are characteristic of all normal profiles, and it is seen that they are not paralleled by the percentages. The high percentages of oak (*Quercus*) at all depths show that this tree had been dominant through the whole of the time covered by the pollen record. In view of the fact that oak is usually under-represented by its pollen, this must represent complete ecological dominance of oak. Associated with the oak are holly (*Ilex*) and hazel (*Corylus*), both occurring consistently through the profile. These are species which could have been growing beneath the oak canopy, but it is not possible to estimate their abundance since under such conditions they would not flower as freely as in the open. However, since holly does not produce much pollen and hazel is a copious producer, it is not unreasonable to deduce that the holly was the more abundant.

It is interesting to note that the birch (*Betula*) and bracken (*Pteridium*) percentages increased in the uppermost layers, suggesting that towards the end the forest had become somewhat more open in canopy. However, this could not have been sufficient to produce clearings because the grass (*Gramineae*) percentages showed no reaction.

This is a pollen profile characteristic of more or less undisturbed forest of long standing. There is, however, no indication in the analyses themselves of the time covered by the pollen record.

2. *Matley Wood*

Today this site is an oakwood with trees up to 250 years old, growing on an acid brown forest soil. Here, too, the main concentration of pollen is in the surface horizons, but unlike the last example the percentages fluctuate violently down the profile.

The high percentage of oak at the surface is a reflection of present conditions, but this is rapidly replaced by bracken in the samples below, bracken reaching a peak percentage at 5–6 in. Below this the bracken is replaced by grasses, which remain preponderant as far down as the record goes. They are accompanied by plantain (*Plantago*) and Compositae pollen, characteristic plants of cultivation. Cereal grains occur throughout the profile. In the lowest levels hazel increases in importance.

This sequence may be interpreted as follows. When the record starts the site was in cultivation, though remnants of hazel scrub still persisted in the neighbourhood. This scrub gradually disappeared; there was perhaps some local regrowth of oak near the site since the percentages and frequencies both show an increase between 8 and 12 in. About the same stage bracken came in on the site and the grasses started to diminish, suggesting that the cultivation had stopped and the land had been

abandoned. Bracken attained absolute dominance, but was then replaced by forest. There is some suggestion of a pioneer pine (*Pinus*) phase with a little birch, but the oak soon became dominant and remains so to the present.

A point to notice in this analysis is the absence of any phase where heather (*Calluna*) was dominant; the values shown are low for this copious pollen producer, and if it ever occupied the site it was certainly subordinate to other vegetation types.

3. *Suffield Moor*

At the time of sampling this was a piece of heather moor, with an old pine plantation about 100 yds. away to the east. Other species are lightly scattered in the vicinity. The soil is a thin iron-pan soil.

The pollen spectrum of the raw humus layer closely reflects this condition, heather pollen being in great excess, but accompanied by birch and pine in small quantities. Grass pollen is the second most abundant species; this is usual in such situations.

The sharp contrast in this spectrum with that of the surface of the mineral soil is no doubt a reflection of the repeated burning off of raw humus. There is very little heather pollen in the mineral soil, proving its status as a late invader, and it is reasonable to assume that when it did come in it would start to produce raw humus which would at once be susceptible to fire. Consequently, the record of this and subsequent intermediate stages is lacking. This is the normal condition in heathland or moorland soils with raw humus. In the mineral soil the pollen analyses show two ecologically incompatible groups—grasses and herbs on the one hand, and woody species, hazel, alder (*Alnus*), birch, and oak on the other. We have seen that a low vegetation may collect pollen from a distance, whereas in a wood this effect is negligible. We may deduce, therefore, that here was a clearing in woodland, a plot of cultivation in a matrix of scrub woodland. Still farther down the profile the grassland species disappear, leaving only the woody vegetation and its accompanying ferns (*Dryopteris*, *Polypodium*, *Pteridium*).

Though there is little in this analysis which permits any dating, it may be assumed tentatively, on the basis of other evidence presented elsewhere, that the record perhaps dates back to the end of the Atlantic period or the beginning of the Sub-boreal period, with Bronze Age farming coming in later in the Sub-boreal. The formation of raw humus probably started at the beginning of the Iron Age, so that there is a large gap between then and the time covered by the present thin layer of raw humus.

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APPENDIX

Method

1. Take about a matchboxful of soil for each sample.
2. Oven-dry the samples as soon as possible.
3. Grind lightly with a pestle and mortar and sift through a 1-mm. sieve.
4. Weigh out from 0·5 g. (surface layers) to 3 g. (mineral subsoil) of soil into a 50-ml. conical flask.
5. Add approximately 10 ml. 10 per cent. NaOH and simmer gently for 40–60 minutes (the longer time for more humus-rich samples).
6. Centrifuge, wash, and centrifuge again.
7. Transfer to copper crucibles with 10 ml. of approximately 30 per cent. HF; boil for 2–3 minutes.
8. Transfer to plastic (Lusteroid) centrifuge tubes, centrifuge and decant.
9. Add 10 ml. 10 per cent. HCl. Transfer residue to glass centrifuge tubes, warm, but do not boil, centrifuge and decant.
10. Add a few ml. glacial acetic acid. Centrifuge and decant.
11. Add about 5 ml. freshly made up acetolysis mixture (9 part acetic anhydride, 1 part conc. H_2SO_4; add H_2SO_4 drop by drop, vigorously agitating the mixture all the time). Bring to the boil. Centrifuge.
12. Add a few ml. of glacial acetic acid; centrifuge, wash and centrifuge again.
13. Transfer again to conical flasks and simmer for 10–15 minutes with 10 ml. 10 per cent. NaOH. Centrifuge and wash twice.
14. Make up to 5 ml. (or a smaller known volume if the material is poor in pollen) with 1:1 glycerol and water to which 0·5 per cent. safranin has been added in the proportions 1:50.
15. Using a hypodermic syringe calibrated for drop-size, place one drop on a microscope slide and cover with cover-glass.

This procedure, being quantitative, allows pollen frequencies as well as percentages to be calculated from the counts obtained.

TRANSPORTED MATERIAL IN THE SOIL PROFILE

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Summary

In the course of a long series of investigations of acid soils by means of pollen analysis, it has been found that about a third of the soils studied contained old levels, more or less disturbed, buried beneath a later deposit of sand or gravel. Two of them were in soils buried beneath Bronze Age tumuli. The depth of covering was always less than 18 in., averaging about half that depth, so that the junction came within the present soil profile. It lay in the A_2, B, or C horizons according to circumstances and was often indistinguishable in the field.

In about half the cases the pollen analysis suggested that the level which had been covered was a forest phase, and there is some indication that this may have occurred towards the end of the Atlantic or beginning of the Sub-boreal period. One example is Late-glacial in date and others post-Atlantic or even recent.

There was close correlation at one site between the activities of Mesolithic man and subsequent soil movement and it cannot be ruled out that disturbance of the forest climax may be the ultimate cause of this phenomenon in other cases too.

With only one exception, wherever the pollen data suggested a forest environment the soil was unbleached.

THE investigation of nearly forty soils by means of pollen analysis has shown that in about a third of them the upper layers are made up of material which has been deposited on the site during the Post-glacial period, presumably by some form of aggradation. In some cases the boundary between transported soil and material *in situ* is invisible morphologically, whilst in other cases it is masked by later soil developments; rarely is it an obvious feature of the profile. The aim of this paper is to present the evidence for the existence of these boundaries and not to assess the pedological implications. The boundaries occur in various types of acid soil, and it will be shown that they may affect subsequent profile development.

The normal pattern of pollen distribution down a profile is that there is a large quantity at the surface, but that the amount falls rapidly with depth (Dimbleby, 1957, 1961). The change in quantity with depth is gradual, and even when there is an increase with depth, as may be found with ancient species, there is no sudden break in the distribution curve. If, however, an old surface becomes buried under newly deposited material it will show in the pollen analyses as a sharp break in the curve, due to the contrast in the pollen content of the new material and the old surface. In this way the old soil surface beneath an earthwork can be located precisely (e.g. Chick's Hill Barrow, Ashbee and Dimbleby, 1959). Occasionally it may happen that the transported material is more acidic and richer in pollen than the soil which is covered; in such a case the boundary is still clearly marked by a sharp difference in pollen frequency, though in the inverse relationship. Another fact which may point to the existence of a buried surface is a sharp change not only in the quantity of pollen but in its composition;

in other words, the pollen spectra above and below the surface may be different.

If a sample happens to cut across a surface, the distinction may not be so clear, but allowance can be made for this. A division may also be blurred by the downward movement of pollen from above, but this effect is relatively unimportant where the buried surface is rich in pollen because pollen moving down from above is masked by the larger concentration below.

We are concerned here with burial by natural and not artificial processes (though human agencies may have played an indirect part in bringing the process about). Clear examples have been found of such buried levels in the soil beneath Bronze Age barrows (Chick's Hill; Reasty Top); others are in soils which have no connexion with earthworks. They have been found in Yorkshire, in Dorset, the New Forest, and Kent—in other words, wherever pollen analysis has been applied to soils. In the majority of cases the transported material is sand, but this may be a reflection of the fact that sandy sites have predominated in these investigations; in two cases the transported material was gravel. In all cases, with the possible exception of Chick's Hill, soil creep could have occurred. By their nature, sandy and gravelly soils may be prone to such soil movement.

The depth of material transported varies from 4 to 17 in. of mineral soil, and in at least one case (Oakhanger) the process has happened more than once. The buried layer is not always clearly recognizable as a surface or as a soil, presumably due to disturbance during the period of change and instability. For this reason the term 'buried levels' is preferred to either 'buried surfaces' or 'buried soils'. At Burley Heath there is a succession of narrow zones perhaps representing surface flood deposits.

As will be seen from Table 1, these levels may appear in various horizons of the present soil profiles. If they are shallow they may be in the A_2 horizon of the present soil, though in areas of thin iron-pan soils such as the Tabular Hills, shallow levels may coincide with the iron-pan itself: presumably the pan forms at the interface. Where they occur in the A_2 horizon, it is impossible to say what the condition of the buried level was before it was covered, but where they occur in the B or C horizons, one can see whether or not it was bleached. In fact, only one of the five levels so situated showed evidence of previous bleaching; that was the Keston example, which had developed in a gravel which had produced a well-developed iron-humus podzol under deciduous forest (Dimbleby, unpublished). In some of those examples where the level occurred in the A_2 horizon, the present A_2 horizon is unusually deep, suggesting either that the new A_2 horizon has developed on top of an old one, or that the old topsoil itself was liable to bleach, so that the newly developing A_2 horizon became extended in depth (Chick's Hill; Pondhead).

The pollen preservation of these buried levels is often not good, possibly because they were buried before acidification, and therefore pollen preservation, had reached the present degree (e.g. Oakhanger).

Consequently, the pollen spectra may show an inflated proportion of resistant types, e.g. lime or fern spores (*Dryopteris* type, *Polypodium*). However, there is a suggestion in several of the levels that they are of Atlantic (zone VII*a*) date; this is corroborated for the first phase of soil movement at Oakhanger by C14 measurements (Rankine and Dimbleby, in press). It also agrees with the occurrence of these buried levels in the natural soil beneath Bronze Age barrows—soil which, in one case at

TABLE 1
Buried Levels

Site	National grid reference	Depth (in.) from mineral surface	Material		Soil horizon	Pollen counts		Forest cover	Predominant pollen and spores
			Above	Below		• NTP	• TP		
Bickley Moor	44/904907	16	Sand	Sandy clay	C	16	38	F	*Dryopteris, Corylus*
Burley Heath	41/211051	14	Silt	Silt	B/C	14	80	F	*Tilia, Alnus, Corylus, Dryopteris*
Chicks Hill Barrow	30/869859	10	Gravel	Sand	A_3	88	76	(F)	Ericaceae, *Tilia, Corylus*
Cock Heads	45/727016	7	Sand	Sand	A_2	296	8	—	Gramineae, Ericaceae
Coldharbour	30/905899	5	Sand	Sand	A_2	295	1	—	Ericaceae, 'W'
Decoy Heath	30/917920	6	Sand	Sand	A_2	148	2	—	*Myrica, Corylus,* Ericaceae
Keston Common	51/418639	13	Gravel	Gravel	B	87	162	F	*Quercus, Corylus, Ilex, Pteridium*
Oakhanger—The Warren	41/775356	6	Sand	Sand	A_1/A_2	229	11	—	*Cf. Hedera, Corylus*
Pondhead	41/312075	17	Sand	Sand	A_2/B	263	16	—	*Myrica*
Reasty Top Barrow	44/965943	6	Sand	Sand	B	50	195	F	*Tilia, Dryopteris*
Suffield Moor-Birch	44/972929	6	Sand	Sand	B	48	94	F	*Corylus, Alnus,* Graminese
Troutsdale	44/920887	4	Sand	Sand	A	534	34	—	Ericaceae, *Corylus,* Graminese

• NTP and TP = Non-tree pollen and tree pollen respectively.

least, had undergone considerable profile development subsequently (Chick's Hill). It might be suggested tentatively that Burley Heath, Chick's Hill, Oakhanger, and Reasty Top are of this date. Others are less easy to place, though if the evidence of Benrath and Jonas (1937) is accepted, that there was a marked increase of sweet gale (*Myrica*) during the Atlantic period, this might be cause for putting Pondhead and Decoy Heath in the same period. However, sweet gale may become dominant for local ecological reasons even today, so the case is not strong.

The proportion of non-tree to tree pollen in these possible Atlantic levels in every case except Oakhanger (where hazel was dominant) indicates the existence of forest or near forest conditions. The observed ratios are not thought to be the result purely of differential preservation of pollen, because some of the non-tree pollen is itself resistant to decomposition, especially the Ericaceae and the grasses. In fact, these two groups dominate the buried level at Cock Heads which contains Late-glacial pollen and is by far the oldest of these buried levels. Godwin (1958) has described and interpreted this analysis in some detail, but did not recognize that the Late-glacial pollen occurred in a buried level; this may mean that there is a chronological break at this level for which he has not allowed.

Other examples are undoubtedly post-Atlantic in date; this certainly applies to the Troutsdale profile (it is on a steep slope) and probably also to the two examples from the Wareham area—Coldharbour and Decoy Heath, if the NTP/TP percentage is any guide. (The pollen type labelled 'W' in the Coldharbour analysis has so far resisted identification by authorities both in this country and on the Continent.)

In five examples one species is highly represented in the top layer of the buried level, but fades rapidly with depth. This is the characteristic pattern of pollen distribution of a contemporary species recently established and suggests that these species had become important shortly (in relative terms) before the old surface was overwhelmed. In two cases the identity of this species is in doubt, the unknown 'W' at Coldharbour and the cf. ivy at Oakhanger. Sweet gale occurred in this way at Pondhead and at Decoy Heath, whilst heather showed a similar behaviour in the Late-glacial Cock Heads site. It is premature to draw any ecological conclusions from this varied and uncertain list.

From these investigations it is not possible to say how extensive was such soil movement. Two soil profiles were examined at Pondhead, separated by several yards, and both showed the same pattern. However, the level at Bickley Moor, which was visible in the subsoil, was dissected out and found to be of limited extent, becoming contorted and diffuse after a few feet in each direction. I have reported a similar layer of buried charcoal in Silpho Moor in north-east Yorkshire (1952), but not realizing how general this phenomenon was, nor having pollen analyses available, I tentatively regarded it as a Pleistocene relic. Such an assumption is plainly unnecessary in the light of evidence of Post-glacial soil movement which we now have.

In the Bickley Moor section the buried level was marked by a line of charcoal, burnt stones, and reddened sand (confirming that the level was not bleached at the time of the fire). In the pollen analyses the layer stands out clearly by the increase in pollen frequency, though the actual flora at the time is not clearly indicated by the pollen spectrum; there is an excessive representation of the resistant fern spores, but the relative proportions of the other pollen types indicate woodland conditions. The charcoal was mainly oak with a little hazel. Whether the burning was natural or anthropogenic it is impossible to say; the site was examined by an archaeologist and proclaimed devoid of any sort of artefact.

At Oakhanger, however, the buried levels (see later—only one level comes within the pollen diagrams) were definitely associated with Mesolithic activity. It was demonstrated that forest clearance had been accompanied by soil acidification and the use of fire on the site was well established. Under these conditions of local environmental deterioration, some form of soil movement may well have been instigated. How general such a human influence could have been in the pre-farming eras it is not yet possible to say, but in contradiction of the generally held view that Mesolithic man left his environment untouched, I have clear evidence from pollen analysis that locally, at any rate, he drastically modified his environment.

It would be unwarrantable, therefore, to assume from these examples

that these levels indicate periods of wetter climate and greater soil creep than now, without taking into account possible anthropogenic influences on the vegetation. One of the few references in the literature to similar phenomena is given by Jonassen (1954) who described the onset of wind-blow in sand at the beginning of the beech period in Denmark. However, he did not attribute this to any particular cause. Another factor which may produce a local effect of this sort is the windthrow of trees, but at present there is insufficient evidence upon which to judge its contribution.

Finally, one immediately wonders whether there is any evidence of whence the transported material has come. We do not know for certain what type of transport is involved, though water is undoubtedly the agent in some instances. Moreover, the evidence would of necessity be negative, and therefore difficult to recognize. However, a few examples have been encountered of soils which have given normal pollen data from the top inch or two, but deeper than that pollen has been totally lacking. These may be soils which have been truncated and only show pollen from the regrowth phases. In some instances there can be no doubt that the soils have been highly acid for a very long time, so that pollen could have been preserved, and in one case—on Burley Heath—such a profile was found not far from one of the buried surfaces. However, such relationships demand much more investigation before they can be fully co-ordinated with each other.

Site Notes

Bickley Moor (*Tabular Hills, Yorkshire*)

Where sampled, the buried level occurred at a depth of 19–20 in. below the present surface, but over its whole extent it fluctuated from 12 to 27 in. in depth. It always lay well below the thin iron-pan at 5 in. It was found to extend only a few feet in each direction, becoming diffuse in one direction and ending abruptly in another. There had clearly been disruption of the surface since it was the seat of a fire.

The surface was marked by fragments of charcoal, mostly oak but with a little hazel, and finely divided charcoal was mixed with sand above. The mineral soil at the buried level was an orange granular clay with grit stones, some of the latter being reddened by fire.

The pollen analysis of this buried level showed an increase in frequency at the level itself, but this was made up mainly of fern spores (*Dryopteris* type) and hazel. There was a small representation of lime, oak, and alder among the trees, but the non-tree species were poorly represented, and then only by grasses and plantain. The NTP/TP percentage signified forest conditions.

Burley Heath (*New Forest*)

Here there was a complex of buried levels from 8 in. depth downwards. They occurred in the lower part of the sandy A_2 horizon and in the B horizon of this gley podzol, and were indistinguishable by eye. No interpretation of the pollen spectra of the successive layers is possible,

but the sharp differences between spectra indicated the separate origin of each layer. Not until the lowest and most clear-cut layer was reached was any interpretation possible. This clearly indicated forest conditions, with lime, alder, oak, and hazel as the main species, accompanied by a small amount of heather and a high proportion of fern spores.

Chick's Hill Barrow (*Dorset*)

This level occurred 10 in. below the Bronze Age surface buried beneath the tumulus. It was marked on the pollen diagram by a sudden increase in the frequencies of a number of species and a sudden change in the percentages of some (alder, lime, grasses). Again lime formed a major component of the tree pollen at this level, accompanied by alder, oak, and hazel. On the other hand, there was a good proportion of heather pollen and bracken spores, and the proportion of NTP to TP suggested conditions of forest with clearings in it.

The buried level lay in the A_2 horizon of a prehistoric, immature humus-iron podzol; the material both above and below the level was gravel. The overall depth of the A horizon of this soil was 17 in., the buried level occurring at 10 in.

The site is on a small hill and whilst there is slightly higher ground to the west, soil creep seems to be only remotely likely.

Cock Heads (*Cleveland Hills, Yorkshire*)

This example occurred at the highest altitude (1,300 ft. O.D.) and was the oldest of all the buried levels so far located. It lay at a depth of 7 in. below the surface of the mineral soil, and 3 in. above the B horizon of an iron podzol, and was indistinguishable in the profile. The pollen analysis showed a sudden increase in the quantities of heather and grass pollen in the upper inch of this buried level, but below this the heather dropped and the grasses were dominant at much higher frequencies and percentages than in the material immediately overlying the level. Apart from a small amount of hazel, and less of birch, the representation of woody species was negligible.

The most interesting feature of this level was the occurrence of traces of a number of species characteristic of the Late-glacial period, notably *Armeria*, *Polemonium*, *Polygonum bistorta*, *Thalictrum*, *Valeriana*, *Botrychium*, and *Lycopodium*. These, taken together with the treelessness of the pollen spectrum, showed that this level dated back to a period before forests spread in Britain after the last retreat of the ice (see Godwin, 1958).

FIGS. 1 and 2

Selected portions of analyses to show the occurrence of buried levels. Each histogram is double, the left-hand side representing absolute frequency (grains/gm. soil), and the right-hand side percentages (of total pollen+fern spores).

Symbols: A, *Alnus* (alder); B, *Betula* (birch); Q, *Quercus* (oak); T, *Tilia* (lime); C, *Corylus* (hazel); I, *Ilex* (holly); E, Ericaceae; G, Gramineae (grasses); PL, *Plantago* (plantain); D, *Dryopteris* type (ferns); PO, *Polypodium* (polypody—a fern); PT, *Pteridium* (bracken). 1, cf. *Arctium*; 2, *Armeria*; 3, Caryophyllaceae; 4, Onagraceae; 5, *Polemonium*; 6, *Polygonum bistorta*; 7, Rubiaceae; 8, *Succisa*; 9, *Thalictrum*; 10, *Valeriana*; 11, *Botrychium*; 12, *Lycopodium*.

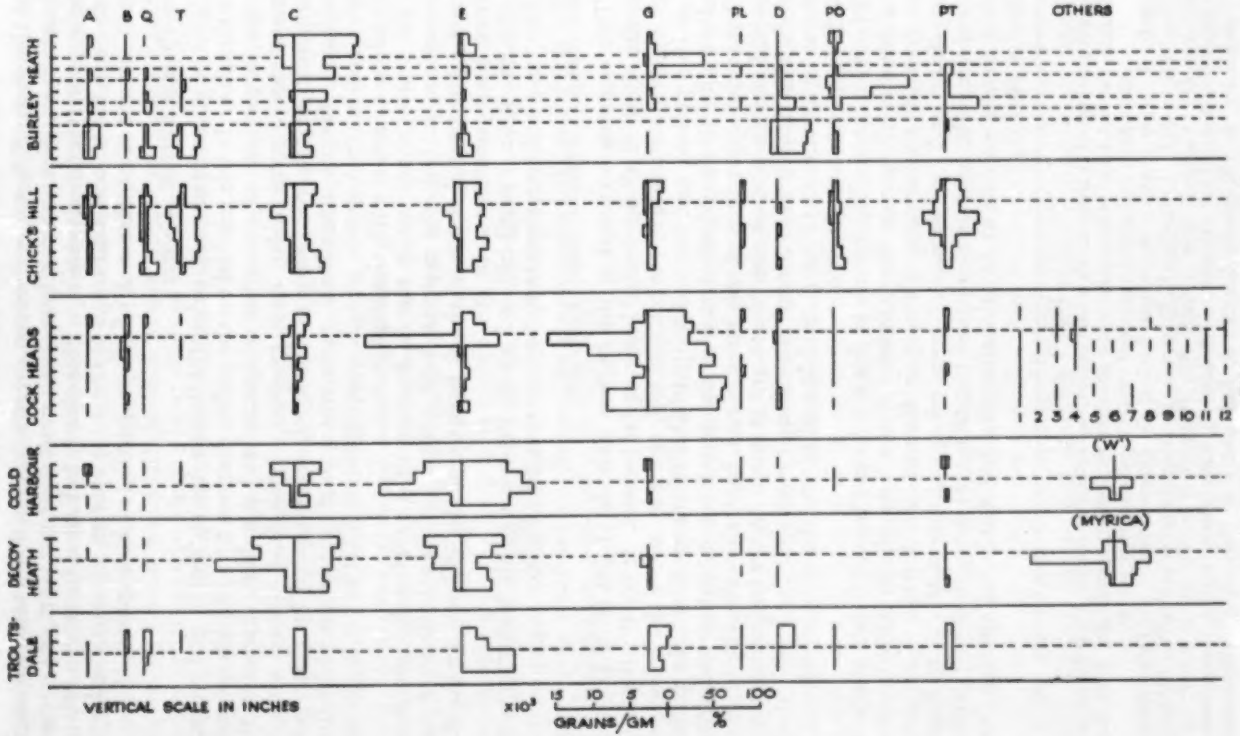
A
B Q
T
C
E
G
FL
D
PO
PT
OTHERS
BURLEY HEATH
CHICK'S HILL
COCK HEADS
COLD HARBOUR
DECOY HEATH
TROUTS-DALE
1 2 3 4 5 6 7 8 9 10 11 12
(W')
(MYRICA)
VERTICAL SCALE IN INCHES
x10³
15 10 5 0 50 100
GRAINS/GM
%

FIG. 1.

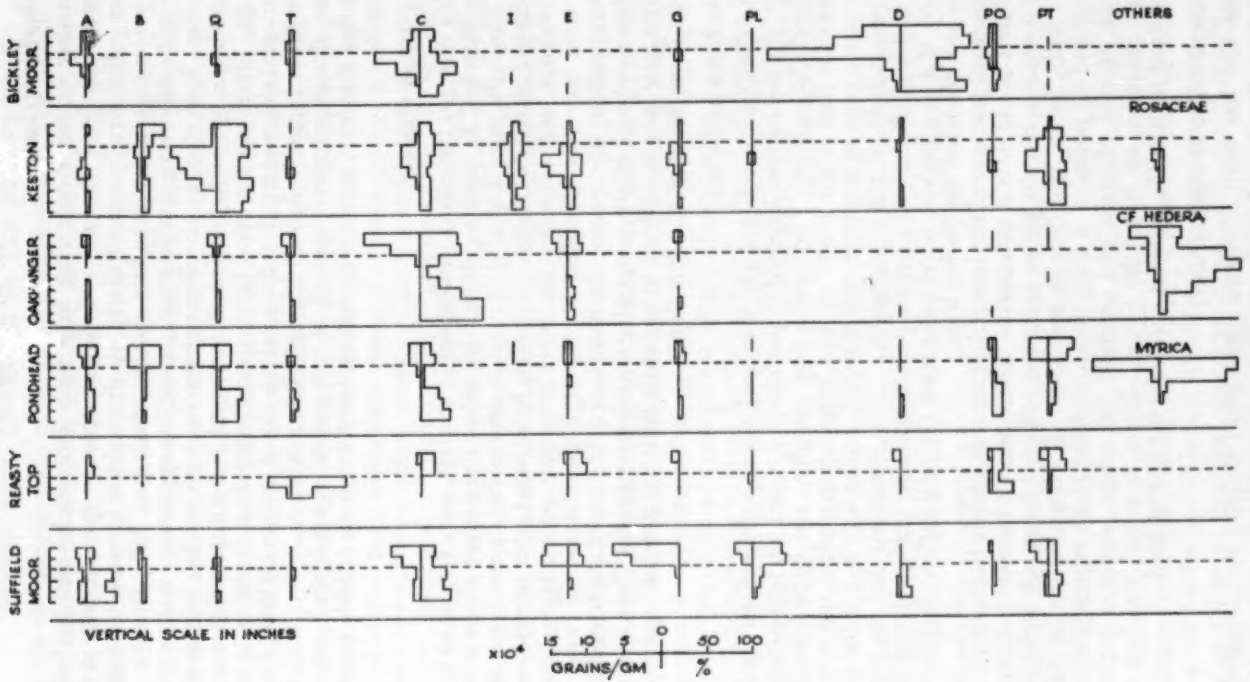
A
B
Q
T
C
I
E
G
PL
D
PO
PT
OTHERS
BICKLEY MOOR
ROSACEAE
KESTON
CF HEDERA
CAW ANGER
MYRICA
PONDHEAD
REASTY TOP
SUFFIELD MOOR
VERTICAL SCALE IN INCHES
x10⁴
15
10
5
0
50
100
GRAINS/GM
%

FIG. 2.

Coldharbour (*Dorset*)

Another example occurring in a deep intensively iron-leached A_2 horizon, this level also was indistinguishable by eye. It was marked in the pollen diagram particularly by the sudden increase in quantity and percentage of an unknown species labelled as 'W'. Being a very large and easily recognizable grain, its sudden appearance was very conspicuous. Nevertheless, the dominant pollen type was heather, as in the layers above, but at the surface it increased in both quantity and percentage. Hazel, on the other hand, though abundant in the top 5 in. of the mineral soil, was much reduced at the top of the buried level, though in the lower layers it showed higher values again.

The almost complete absence of tree pollen, apart from hazel, suggests that this level is relatively recent, but there is no reliable means of dating it.

Decoy Heath (*Dorset*)

This example had many similarities to the last, occurring in an intensively bleached A_2 horizon, about 6 in. below the surface of the mineral soil. Similarly, too, it was very poor in tree pollen, apart from hazel, and cannot be reliably dated. However, hazel was better represented in this instance, and exceeded the other abundant pollen type, heather. The level was best identified by the high percentages of sweet gale (*Myrica*) pollen; this species was dominant at the top of the buried level, but decreased with depth, suggesting a temporary phase. The occurrence of sweet gale here is difficult to reconcile with the present topography; the site is on the crest of a low ridge.

Keston Common (*Kent*)

Like the Chick's Hill example, this level was also covered with gravel; in fact, the soil section, exposed in the face of a gravel pit, was composed of gravel throughout. The profile was complex; the buried level lay towards the base of the B horizon of a humus-iron podzol, but below it there was a zone of less iron-rich material, giving way at greater depth to a second zone of iron accumulation. This suggested that the buried level had itself developed a podzol profile, but after being covered the B horizon of a new podzol, developing from the new surface, had formed across and obscured the buried level.

This level gave one of the best pollen records, clearly indicating forest conditions at the time it was buried. There was an increase in quantity of most species, but the pollen spectrum reflected dense oak forest, with hazel, holly, birch, and lime as associates. A somewhat earlier phase, represented by pollen at a great depth, showed more representation of heather, grasses, plantain, and bracken; this might suggest a period of human influence on or in the forest. Birch, however, was less well represented than in the material overlying the buried level.

Oakhanger—The Warren (*Hants*)

This site has been discussed elsewhere (Rankine and Dimbleby). There were two buried levels; one, in a pollen-free zone, was detectable

only by the stratification of artefacts and charcoal. The second, even better marked by stratified flints and charcoal, showed clearly in the pollen diagrams. In the soil profile, a humus-iron podzol, it coincided with the base of a zone of humus staining in the deep A_2 horizon, but was otherwise not marked by soil morphological differences.

Palynologically the level was marked most clearly by the high proportion of pollen which has been identified as ivy, but as ivy only produces small amounts of pollen, it is difficult to see how concentrations such as this (an even more dramatic example is known) could be explained. The pollen has therefore only been named tentatively.

Pollen preservation in the buried layer was much poorer than in the covering sand, so the boundary was marked by a sudden decrease in frequency with depth. Below the buried surface, in which the cf. ivy pollen formed the characteristic curve of a recent species, hazel becomes predominant, with a certain amount of heather and consistent occurrence of alder, lime, and oak pollen. The vegetation of the time was probably hazel scrub, with remnants of high forest still persisting, but with clearings in which heather was growing. This occurred during the Atlantic period (zone VII*a*). The first buried level, referred to at the beginning, was probably overwhelmed somewhere around the Boreal/Atlantic transition (zones VI*c*/VII*a*).

Pondhead (*New Forest*)

Pondhead, like Oakhanger, was another case in which the buried level was less pollen-rich than the sand above it. Nevertheless, the break in sequence is unquestionable, and was marked particularly by a high concentration of sweet gale pollen, totally absent in the samples above, and seemingly only of short-lived dominance. Below it the pollen record showed an earlier forest phase, with oak dominant, but hazel abundant, and alder and lime also present. In contrast with the forest phase represented above the buried level, birch, holly, and bracken were unimportant, suggesting a different forest type.

At Pondhead the buried level boundary fell at the top of the present B horizon, at any rate where the samples were taken; where the B horizon dipped, it probably fell within the A_2 horizon. In any case, the mineral soil at this level was intensively leached of iron. The boundary was quite indistinguishable visually in the field.

Reasty Top Barrow (*Tabular Hills, Yorkshire*)

Though palynologically this was a very well-defined buried level and in the profile it was marked by the formation of an incipient thin iron-pan of the soil buried beneath the Bronze Age barrow, yet little of value can be deduced from it. Pollen counts were only just obtainable from the top 2 in. of the level, and such pollen as there was, was of types resistant to decay—fern spores and lime. Though it is likely that the absence of grass and heather pollen is real, since these are not evanescent types, there was no means of assessing the composition of the forest except to say that lime must have been an important component.

The soil was unleached at the time of covering, and the date must be

Atlantic or early Sub-boreal (VII*a* or VII*b*) since the level occurred beneath a Middle Bronze Age tumulus.

Suffield Moor—Birch (*Tabular Hills, Yorkshire*)

Situated within a mile of the last site, on the same plateau, this example also showed the formation of a thin iron-pan at the junction of the buried level and the overlying sand.

The pollen content of this level was much lower than that of the material above, and the boundary showed up both on this account and because of a sharp change in percentages of certain species. Alder and hazel formed much higher proportions than above the pan, and the fern spores followed suit. On the other hand, the Ericaceae and the grasses, the main groups occurring above the pan, were poorly represented below; in fact, the Ericaceae pollen was only found in the upper part of the buried level, clearly showing that this group had not always been on the site.

Though lime and oak were represented in small quantity, there was no good evidence here of the high forest state.

Troutsdale (*Tabular Hills, Yorkshire*)

This site, a mixed oakwood, was on a steep slope flanking the west side of Troutsdale. Being an early analysis, no absolute frequencies were determined, the pollen diagram representing only percentages.

The sand both above and below the buried level was unbleached, but visually the level could be detected by different humus staining. From the diagrams the boundary was clearly indicated by a sudden increase in the percentages of Ericaceae pollen and decreases in oak, elm, grasses, and ferns, as compared with the overlying material. It is probable that this was a recent burial and indeed may be connected with cultural operations when this wood was established.

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A PODZOL DEVELOPMENT SEQUENCE IN OAKWOODS AND HEATH IN CENTRAL ENGLAND

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Summary

A sequence of soils is described from a slightly podzolized sandy brown earth to humus–iron podzol. In this gradual degradation sequence morphological and chemical evidence is presented to suggest that the following succession of soil processes is involved:

(*a*) translocation of clay;

(*b*) chemical weathering of the A_1 horizon resulting in an association of iron with organic matter, and slight eluviation of iron: the stage of podzol intergrade;

(*c*) strong iron eluviation: the stage of iron podzol;

(*d*) eluviation of organic matter, which rests on or is incorporated in a previously developed iron B horizon: the stage of humus-iron podzol.

Pollen analysis has helped to establish that podzolization can occur under oakwood where edaphic environments favour the accumulation of thick, moist, strongly acid organic layers.

THE status in classification of many British soils is difficult to assess owing to extensive biotic effects. Deforestation, followed by ploughing and grazing, have altered the soils physically and chemically and changed their ecological relationships. In consequence there are few, if any, areas of natural vegetation, e.g. virgin forest, and relatively few areas of semi-natural vegetation. The importance of such sites is therefore often disproportionate to their size, as it is only in sites which most closely approach natural conditions that we can expect to discover the true relationships between natural vegetation and soil morphology.

Evidence of podzolization[1] under oak conflicts with widely held views of the effect of this type of vegetation on soil formation. Dimbleby and Gill (1955), however, refer to mor humus formation under old oaks in the New Forest, where they noticed visible signs of leaching, though at the same time they state that there was no evidence to suggest that continuous oak forest produced a podzol. Anderson (1951) noted signs of degradation on infertile sites under *Quercus petraea* and *Q. robur*, and similar podzolized horizons have been seen by the author under old oaks in Sherwood Forest. In his comprehensive study of the genus *Quercus* in Britain, Jones (1959) states that on the most nutrient-deficient soils derived from highly siliceous rocks, usually podzols or gley podzols, *Quercus petraea* is generally the principal species. *Betula* sp., *Sorbus*

[1] The definition of podzolization used here involves the reactions concerned in the movement and accumulation in the soil profile of sesquioxides and organic matter in freely drained conditions and under raw humus horizons. These reactions although incompletely understood include (i) the breakdown of clay minerals in the A_1 horizon leading subsequently to differentiation of silica and sesquioxides, (ii) the mobilization of iron in A horizons in association with acid products of organic decomposition, (iii) the deposition of iron and organic matter in B horizons.

aucuparia, and *Ilex aquafolium* are the only associated tree species and under natural conditions the last two would probably be more abundant than they usually are. In the Killarney oakwoods (Turner and Watt, 1939) in an oceanic climate with high rainfall, the *Quercetum-ilicosum* is associated in places with strongly developed podzols. Kubiena (1953) states that iron podzols develop under acid-tolerant oakwood in north Europe, and Scurfield (1953) describes mor, developed under *Quercus petraea*, *Betula pubescens*, and *Deschampsia flexuosa*, in the south Pennine woodlands.

Deciduous forest with the exception of beech (Dimbleby and Gill, 1955) has escaped responsibility for podzolization, but a considerable amount of evidence indicates that in the poorest edaphic environments oak can be found in association with mor humus and podzols.

In the case of the sandy soils considered here, Tansley (1953) suggests that the natural vegetation was oakwood, dominated by *Quercus petraea*. In the Midlands few ecological studies have been made on this soil–plant association, the outstanding example being the study of the ancient woods of Sherwood Forest by Hopkinson (1927). However, during a reconnaissance soil survey of the west Midlands, an area of woodland was found, which in general conforms to the sessile oakwoods described by Tansley, though in detail it is apparently ecologically unique. This area is Sutton Park (Warwickshire), which consists of about 4 square miles of woodland, heath, and grassland, at Sutton Coldfield, east of Birmingham. Sutton Park was given by Henry VIII to Sutton Coldfield in 1528 (Bracken, 1860), when the 500 acres or so of woodland, most of which seems to have been coppice, was enclosed. From pollen analysis which is referred to later there is evidence to suggest that at least part is ancient woodland, and these general conditions provided an ideal opportunity to investigate the soil-vegetation relationships of sandy soils. During the investigation it was found that nearly all the soils within the park were podzols or related soils, and this paper concerns these soils.

Vegetation

The woods of the park, apart from recent plantings, consist of a *Quercus petraea–Ilex* association. Below the oak canopy holly forms a continuous layer and sometimes, together with *Sorbus aucuparia*, reaches the canopy level. This association in close canopy prevents the establishment of a field or ground stratum, except where the light intensity is increased locally by felling or tree fall. Both the holly and rowan are unusually well developed, with the former coppicing extensively from the base. Within the wood dark, moist conditions prevail, whilst on the edges gaps below the oak canopy are infilled by holly, resulting in holly rings similar to those described by Dimbleby and Gill (1955) from unenclosed woodland in the New Forest. Outside the woods many oak seedlings develop, but only rarely do they escape browsing by cattle, whilst within the woods holly successfully regenerates. This structure is quite similar to that of the Killarney woods (Turner and Watt, 1939), though the moist oceanic climate there, and heavier rainfall, has resulted in a bryophyte and lichen woodland floor.

One small area of old woodland, now unenclosed, differs from the general type. It approximates in structure to the dry mixed oakwood of Sherwood Forest, consisting of codominant *Quercus robur* and *Q. petraea* in open canopy with birch, holly, rowan, and gorse. The field and ground strata consist of patches of *Pteridium*, *Vaccinium myrtillus*, and *Deschampsia flexuosa*.

Calluna heath with gorse borders the woodland, generally with an ecotone or tension belt of bracken and birch. The development of this is aided by periodic heath fires, favouring the spread of bracken from the woodland edge over the heath, which in turn prepares a favourable environment for the regeneration of birch.

Other factors influencing soil formation

Although a number of formations are represented on the geological map of the district, the majority afford sandy or gravelly parent materials which may be related to topography in the following simplified manner. Locally derived glacial sands and gravels thinly cover the ridges and valley sides mainly formed of Bunter Pebble beds, which may be described lithologically as sandstones and pebble beds, interbedded. Locally, brecciated quartzite pebble beds, known as the Hopwas Breccias, are exposed in gravel pits, and, finally, a restricted area of red marls referred to the Enville Beds occurs near the northern limit of the park. Isolated patches of boulder clays have also been mapped, though these deposits hardly seem to differ from the glacial sands and gravels.

The average rainfall in the park for the 28 years 1931–58 is 28 in. and the range 21–36 in. Though the mean monthly averages for these years show a double maximum in July–August and November–December, with a range of 1·9–3·0 in., there is a very even spread of rainfall throughout the year. The average potential evapo-transpiration is approximately 18 in. (Penman, 1950).

The average monthly mean temperature for January (1950–9) is 36° F. and for July 61° F.; the monthly average of sunshine hours over the same 10 years is lowest in December at 32, and highest in June at 186 hours.

Soils and Vegetation

The soils identified in this study are all representatives of the major group of podzolic soils, though relic morphological features of *sol lessivé* occur in subsoil layers of some profiles. A genetic sequence of soils, the profile morphology of which has resulted from different environmental effects upon similar parent materials, is presented diagrammatically in Fig. 1. Since they are closely, though not exclusively, linked with particular types of vegetation, they are described in this context as

(*a*) soils associated with close canopy woodland (iron podzols and podzol intergrades);
(*b*) soils associated with open canopy woodland (sandy brown earths—slightly podzolized);
(*c*) soils associated with heath (humus–iron podzols).

Horizon nomenclature follows Kubiena (1953), though since the

interpretation of profile 1 involves the recognition of more than one phase of development, the marks ′ and ″ are used on horizon symbols to denote the lower phases (Grossman *et al.*, 1959).

Although the investigation has been based mainly on morphology, it has been supplemented by the following analytical data.

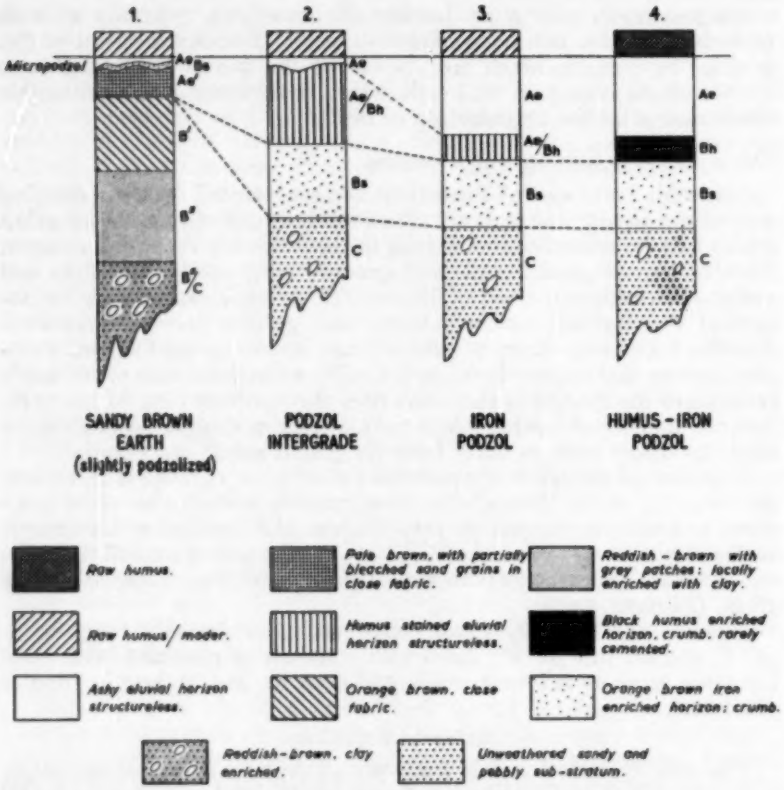


FIG. 1. A genetic sequence of soils on sandy sub-strata.

1. Estimations of free iron in the soils based on Deb (1950), were run in duplicate—(*a*) by normal Deb procedure, (*b*) with a pre-treatment with H_2O_2 followed by washing to remove iron complexed with organic matter, and then normal Deb procedure.

2. Ultimate analysis of $< 2\mu$ clay.

3. Colloidal organic matter was estimated by a double extraction at 100° C. with N/10 potassium pyrophosphate (pH 7·0) and the results expressed as Spekker Units. This method is based on a paper by Bremner and Lees (1949) though the modification by Bascombe is unpublished. Here it provides a measure of the relative amounts of the organic

matter most likely to be involved in the reactions and translocations associated with podzolization.

4. Pollen analysis was used to investigate site history according to methods followed by Dimbleby (1961) and Faegri and Iverson (1950).

TABLE 1

Analytical Data of Soils from Sutton Park

	Genetic type	*Hor. nomenclature*	*Horizon depths (in.)*	pH	C/N	*Mechanical analysis*				1 *Free* Fe_2O_3 (%)	2 *Free* Fe_2O_3 (%)	3 *Coll. O.M. Spekker Units*
						< 0·002 mm.	0·02–0·002 mm.	0·02–0·2 mm.	0·2–2 mm.			
S. Pk. 1	Podzol intergrade	H	..	3·6	21	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		A_e	0–1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0·1	0·1	4·2
		A_e/B_h	1–9	3·7	n.d.	5·5	7·2	45·4	41·9	0·8	0·6	1·6
		B_s	9–14	4·3	n.d.	5·7	3·5	44·1	46·7	1·0	1·0	0·4
		C	14–26	4·5	n.d.	3·8	2·6	44·6	49·0	0·7	0·6	0·2
S. Pk. 11	Iron podzol	H	..	3·4	22					..	..	..
		A_{e1}	0–4	3·6	n.d.					0·1	0·1	1·6
		A_{e2}	4–7	n.d.	n.d.					0·1	0·1	0·5
		A_e/B_h	7–9	3·6	n.d.					0·4	0·3	2·5
		B_{s1}	9–12	3·4	n.d.			No data		1·4	1·3	1·5
		B_{s2}	15–20	3·4	n.d.					1·0	0·8	1·1
		C	> 20	4·1	n.d.					0·4	0·4	0·5
S. Pk. 2	Humus-iron podzol	H/A_e	0–4	3·5	n.d.	3·3	8·0	41·7	47·0	0·2	n.d.	24·2
		A_e	4–8	4·0	n.d.	2·7	5·9	43·1	48·3	0·3	n.d.	3·9
		B_h	8–9½	3·6	n.d.	4·8	7·2	42·6	45·6	0·8	n.d.	18·0
		$B_{h/s}$	9½–18	4·0	n.d.	9·4	6·8	40·5	43·3	2·3	n.d.	5·1
		B_s	18–25	4·6	n.d.	7·3	6·3	41·1	45·3	1·2	n.d.	1·5
		C	> 25	4·6	n.d.	5·8	4·5	65·4	24·3	0·7	n.d.	0·6
S. Pk. 13	Slightly podzolized sandy brown earth	F	..	3·5	21	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		H	..	3·5	21	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		Micro-podzol	0–1½	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
		A_e'	1½–5	3·8	n.d.	7·1	8·2	34·2	50·5	1·3	1·0	0·8
		B′	5–10	4·3	n.d.	6·8	12·9	32·3	48·0	1·3	1·0	0·5
		B″	10–25	4·4	n.d.	11·4	17·4	27·2	44·0	2·0	1·7	0·3
		B″/C	25–32	4·3	n.d.	19·1	15·0	27·3	38·6	2·5	2·5	0·3

1. Modified Deb (soil).
2. H_2O_2 pre-treatment followed by modified Deb.
3. Colloidal organic matter expressed as Spekker Units.

(*a*) *Soils associated with close canopy woodland*

Under the dense shady cover afforded by the woods, decomposition, though not slow, does not keep pace with leaf fall so that frequently 4 in. of organic matter overlies the mineral soil. Roughly equal thicknesses of L, F, and H layers are common, and with an average pH < 4 these horizons strongly resemble raw humus (Kubiena, 1953) though the presence of a well-defined H layer may indicate that the humus form is transitional to moder. Many of the fine tree roots have mycorrhizas and within the humus layers there is a network of fungal mycelia. Collembola, mites, fly larvae, enchytraeids, and root aphids are common mesofauna, but no earthworms were seen throughout the investigation, and only one viable and one non-viable earthworm cocoon. In all the close canopy woodland the soils show a marked development of a bright orange-brown, iron-rich horizon (B_s) though the eluvial horizon (A_e) is not always as obvious. The morphology of these soils is similar to *sol podzolique* (Duchaufour, 1956*a*) for above an obvious iron-enriched

horizon there is no ashy eluvial horizon. However, from profile studies by Duchaufour (1956*b*) *sols podzoliques* are typified by entrainment indices of free iron (B_s/A_e) of about 2–4, whereas in these soils indices of 1·1–1·5 are normal (Tables 1 and 2). Because of uncertainty about the exact equivalent of these soils in European classification systems they

TABLE 2

Free Iron and Organic Matter in Humus-iron Podzols and Podzol Intergrades

		Humus-iron podzols				*Podzol intergrades*		
		1 *Free* Fe_2O_3 (%)	2 *Free* Fe_2O_3 (%)	3 *Coll. O.M. Spekker Units*		1 *Free* Fe_2O_3 (%)	2 *Free* Fe_2O_3 (%)	3 *Coll. O.M. Spekker Units*
S. Pk. 5	A/A_e	0·4	0·3	6·9	S. Pk. 6 A_e	0·3	Nil	2·1
	A_e	0·5	0·4	3·5	A_e/B_h	0·8	0·6	1·4
	B_h	2·2	1·3	15·7	B_s	1·3	0·8	1·8
	$B_{h/s}$	2·1	1·7	8·7	B_s	1·8	1·5	1·2
	B_s	1·3	1·3	0·7	C	0·8	0·7	0·3
	C	1·1	1·0	0·7				
S. Pk. 8	A_e	0·1	0·1	1·7	S. Pk. 7 A_e	0·3	0·1	2·3
	B_h	2·5	1·5	7·5	A_e/B_h	0·8	0·6	1·4
	$B_{h/s}$	2·9	2·0	3·4	A_e/B_h	0·8	0·7	2·2
	B_s	2·2	2·0	2·4	B_s	1·0	0·8	1·3
	C	1·7	1·7	1·2	C	0·6	0·6	0·4
S. Pk. 9	A_e	0·3	0·1	2·5				
	B_h	0·7	0·3	15·4				
	B_s	2·1	1·5	6·7				
	C	1·0	0·8	0·5				
S. Pk. 10	A/A_e	n.d.	n.d.	7·0				
	A_e	0·1	0·1	2·6				
	B_h	1·4	0·4	21·0				
	B_s	2·9	2·4	5·2				
	C	1·3	1·5	2·2				

1. Modified Deb (soil).
2. H_2O_2 pre-treatment followed by modified Deb.
3. Colloidal organic matter expressed as Spekker Units.

have here been called *podzol intergrades*, although it is recognized that they have close affinities with *sols podzoliques*. The following profile (S. Pk. 1, no. 2, of Fig. 1) is representative:

L ½ in. Mainly leaves of oak, holly, birch, and rowan; no ground flora; mycorrhiza on fine tree roots.

F 1½ in. Recognizable remains of leaves and twigs, laminated; network of fine holly roots hold layer together; one enchytraeid worm.

H 1 in. Black, semi-amorphous; friable with some bleached sand grains.

A_e 0–1 in. Grey (10 YR 3/1) loamy sand; with lighter and darker patches, becoming purplish towards the horizon base; horizon is held together by fine tree roots; small quartzite pebbles leave imprints in fabric; sharp boundary to

A_e/B_h 1–9 in. Purplish-grey (5 YR 3/3) loamy sand; the overall colour is that of the fine material coating bleached sand grains; pebbles (¼–8 in.) leave shiny imprints in soil fabric; structureless, numerous roots; merging boundary to

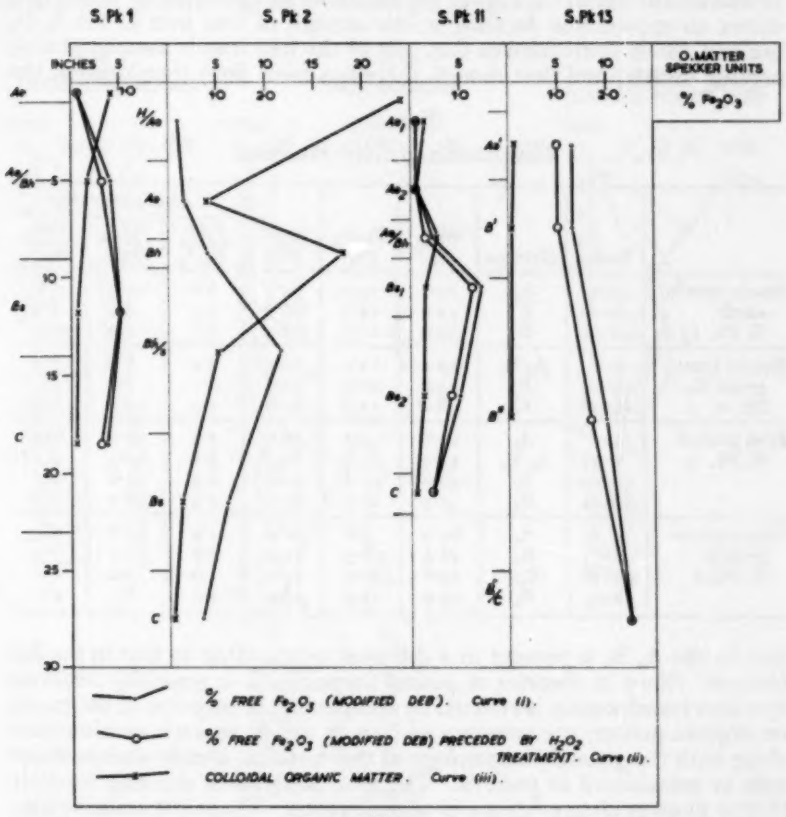

S. Pit 1
S. Pit 2
S. Pit 11
S. Pit 13
INCHES
O. MATTER SPEKKER UNITS
% Fe_2O_3
% FREE Fe_2O_3 (MODIFIED DEB). Curve (i).
% FREE Fe_2O_3 (MODIFIED DEB) PRECEDED BY H_2O_2 TREATMENT. Curve (ii).
COLLOIDAL ORGANIC MATTER. Curve (iii).

FIG. 2

B_s 9–14 in. Orange-brown (5 YR 4/6) sand to loamy sand; stones as above; crumb; fluffy consistence; fine pores and root channels; numerous roots; merging to

C 14–23 in. Reddish (5 YR 5/6) sand; stones as above, very weak crumb and single grain; fine pores; some root channels in upper part of horizon, none below.

Beneath the organic layers there is a thin bleached intermittent horizon, reminiscent of that described as micro-podzol (Lyford, 1952) though, as there is no seam of iron concentration, it may best be described as micro-gley (Manil and Pecrot, 1954). The fabric of the A_e/B_h horizon consists of bleached sand grains set in a finer matrix of purplish-

brown colour, and that of the B_2 horizon sand grains coated with colloidal material rich in iron. The curve for free iron (i, Fig. 2, S. Pk. 1) indicates that there is little eluviation of iron to account for the obvious morphological differences in the field between the A_e/B_h and B_2 horizons. However, the curve (ii, Fig. 2) for the same soil pre-treated with H_2O_2 shows an appreciable decrease in the amount of free iron in the A_e/B_h horizon. This demonstrates that part of the free iron is associated with organic matter, and that though there has been little translocation the

TABLE 3

Composition of Clay Fractions

	Inches	*Horizon*	SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	*Molecular ratios* $\frac{SiO_2}{R_2O_3}$	$\frac{SiO_2}{Fe_2O_3}$	$\frac{SiO_2}{Al_2O_3}$
Sandy brown earth S. Pk. 13	1½–5	A_e'	54·4	15·0	24·3	2·6	9·7	3·8
	5–10	B'	53·0	14·3	26·7	2·5	9·9	3·3
	10–25	B''	50·0	14·3	28·3	2·3	9·3	3·0
Podzol intergrade S. Pk. 1	1–9	A_e/B_h	53·4	15·9	16·9	3·4	8·9	5·4
	9–14	B_2	45·2	17·3	24·6	2·1	7·0	3·1
	14–26	C	48·4	12·9	27·6	2·3	10·0	2·9
Iron podzol S. Pk. 11	4–7	A_e	65·8	3·3	16·6	5·9	52·2	6·7
	7–9	A_e/B_h	53·4	11·6	22·3	3·1	12·3	4·1
	9–12	B_2	46·8	21·4	21·0	2·3	5·8	3·7
	12–20	B_2	50·4	16·9	22·8	2·4	8·0	3·8
Humus–iron podzol S. Pk. 2	4–8	A_e	64·3	5·8	21·0	4·4	29·7	5·2
	8–9½	B_h	48·4	16·9	22·4	2·5	7·7	3·5
	9½–18	$B_{h/e}$	39·6	27·2	24·1	1·7	3·9	2·6
	18–25	B_2	47·6	15·3	28·2	2·2	8·3	2·7

iron in the A_e/B_h is present in a different relationship to that in the BS horizon. Since in theories of podzol formation it is generally believed that iron translocation is effected by complexing or sorption of the metal on organic matter, the presence of iron in the A_e in such combination along with the general morphology of this horizon, clearly stamps these soils as transitional to podzols. The total analyses of the clay fraction (Table 3) gives clear evidence of podzolization. There is a sesquioxide-rich B_2 horizon associated with a more siliceous eluvial horizon. Compared with the data for the iron and humus–iron podzols those of the podzol intergrade are clearly intermediate.

The importance of a determination of the nature of past vegetation in any soil–vegetation study has been amply proved by Dimbleby and Gill (1955). As this investigation was partly concerned with the effect of vegetation on soil formation, it was essential to provide evidence of the vegetation history of the sites, and this was done by pollen analysis.

The present close canopy oak–holly association seems to be of long standing for oak and holly pollens (Fig. 3, S. Pk. 7) dominate the soil layers. The gradual increase in Gramineae and Ericaceae with profile depth suggests that the wood was at one period much more open

and that it gradually changed to the dark moist woodland which now prevails.

On flat and gently sloping sites under the oldest sessile oaks (11–15 ft. girth at breast height) well developed podzols occur locally with strongly bleached A_e and marked iron-enriched B horizons. In the absence of a

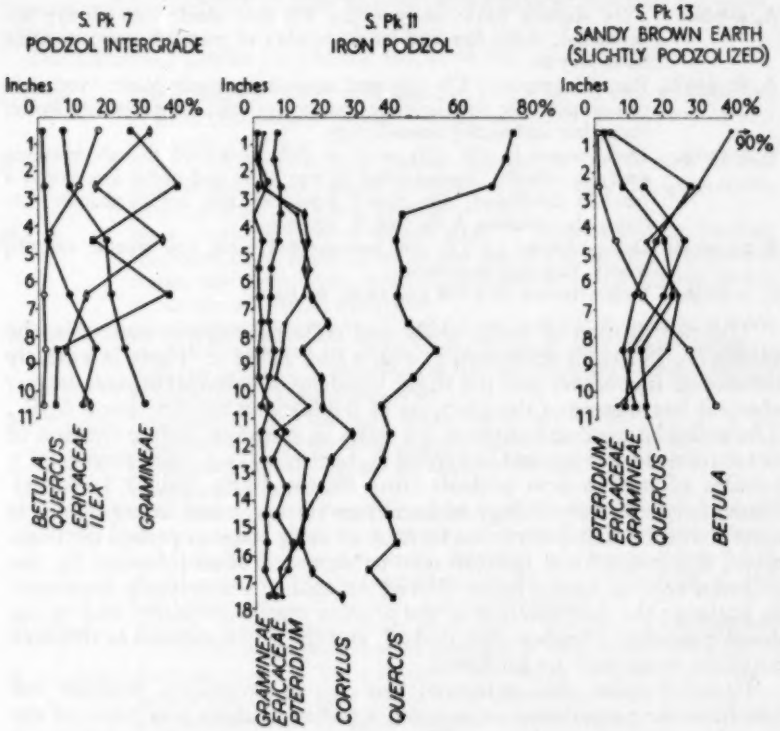


FIG. 3

true organic B horizon the soils are iron podzols and compare with normal iron podzols in central and northern Sweden (Tamm, 1950), and with those described by Kubiena (1953) as widely distributed in north Europe and Scandinavia. The description which follows is of a mature profile (S. Pk. 11, no. 3, of Fig. 1).

L 1 in.	Loose wet litter composed of oak and holly leaves and twigs; much faunal activity, particularly collembola; in lower part of this horizon small roots with mycorrhiza.
F 1½ in.	More compact, wet, dark brown organic matter with leaf and stem remains; many roots with strong association of mycorrhiza; less obvious faunal activity.
H ½ in.	Black compact organic matter which does not separate easily from

inorganic layer below; wet; no recognizable plant remains; no fauna observed.

A_e 0–4 in. Slightly greenish-grey (10 YR 5/2) sand; very stony; very slightly cemented; pebbles leave imprint; many roots including some of 2 in. diameter; mineral and organic material is carried from higher to lower horizons throughout the profile along old root channels; patches of purplish-grey and grey sand; merging boundary to

A_e 4–7 in. Very slightly brownish-grey (10 YR 6/2) sand; very stony; uncemented; roots fine and large; patches of purplish-grey; merging boundary to

A_e/B_h 7–9 in. Purplish-grey (2·5 YR 3/2) sand sometimes nearly black; varying in colour possibly with organic matter content; uncemented; stony; sharp but undulating boundary to

B_s 9–12 in. Dark brown (5 YR 3/6) sand; slightly cemented though breaking easily to crumb; concentration of fine roots and much less stony; a patchily developed, thin (¼ in.) cemented layer occurs sharply outlining the junction A_e/B_h and B_s horizons.

B_s 12–20 in. Orange-brown (5 YR 4/6) uncemented sand, few stones; crumb; friable, fine and large roots.

C > 20 in. Yellow-brown (7·5 YR 4/4) sand; no roots.

The distribution of ferric oxide and colloidal organic matter in the profile (S. Pk. 11) is presented in Fig. 2 and Table 1. There is a clearly developed B_s horizon and the slight build-up of colloidal organic matter above it has suggested the adoption of the horizon nomenclature A_e/B_h. The colloidal organic matter at 2·5 units is, however, only a fraction of the amount that is present in typical B_h horizons (15·5 units average of 5 profiles of humus–iron podzols from Sutton Park, Tables 1 and 2). Since, from the morphology and analyses of the podzol intergrade, it is clear that iron-rich B horizons form at an early stage in podzol development, this transitional horizon may be regarded as an incipient B_h, the colloidal organic matter being filtered out against a previously developed B_s horizon; the continuation of the process would inevitably lead to the development of a humus–iron podzol, and the whole process in this area could be completed under forest.

To substantiate this statement and also to investigate whether oak was here the podzolizing vegetation, a pollen analysis was made of the organic and inorganic layers. The preliminary work indicated that oak pollen was dominant to 18 in., but as this analysis was of critical importance the pollen from separated samples and a sequence of unseparated samples was sent to Dr. Dimbleby at the Department of Forestry, Oxford. His analysis for S. Pk. 11 is shown in Fig. 3. The development of this mature podzol under oak is established beyond doubt by the preponderance of oak pollen and by the minor influence of ericaceous species.

(*b*) *Soils associated with open canopy woodland*

Of the old woodland sites only one corresponds approximately to the dry mixed oakwood of Sherwood Forest. In this case soil development is relatively weak, with only slight indications of podzol intergrade morphology. The acidophilous ground flora consists of patches of *Pteridium*

aquilinum, *Deschampsia flexuosa*, *Vaccinium myrtillus* with *Pteridium* most widespread. Distinct L, F, and H layers may be seen within the 3 in. organic matter which has accumulated at the surface, though the H layer is partly the result of burning. Many fine roots of *Deschampsia*, as well as fine tree roots with mycorrhizas, ramify through the loose bracken litter. The organic horizons with high C/N ratio (21) lying sharply on the mineral soil correspond to raw humus transitional to moder (Kubiena, 1953).

The following profile (S. Pk. 13, no. 1, of Fig. 1) is typical:

L 1½ in.	Loose bracken litter, with oak and rowan leaves; many ramifying roots of *Deschampsia flexuosa*, though few plants; mycorrhiza on fine tree roots, probably holly.
F ½ in.	More compact litter, still mainly bracken; at base of this horizon there is lateral development of rhizomes; still many fine grass roots; no fauna observed; no mycorrhiza.
H 1 in.	Black, well-decomposed organic matter; concentration of bracken rhizomes; some charcoal, many fine bracken roots; one enchytraeid worm; one white mite; zone of bleached sand and organic matter intimately associated, merges to
A_e 0–1 in.	Grey or greenish-grey (10 YR 5/1) loamy sand; this horizon variable in thickness up to 1 in.; held by fine bracken roots, though breaking easily to compact tabular angular blocky structures; some quartzite pebbles; very sharp boundary to
B_s 1–1½ in.	Purplish-grey (10 YR 5/2) loamy sand; sometimes with an ½ in. cemented layer at junction with horizon above; rhizomes and fine grass roots, though neither go much below this level in the profile, merging boundary to
A'_e 1½–5 in.	Pale yellow-brown (6·25 YR 4/4) loamy sand; tight fabric but breaking to crumb; partially bleached sand grains; some fine grass roots; soft Mn/Fe concretions 1 mm. diameter; many rounded quartzite pebbles; no live bracken rhizomes; live (¼ in.) and dead (½ in.) tree roots, fine pores and fissures; merging boundary to
B′ 5–10 in.	Slightly more orange-brown than above; soft Mn/Fe concretions; crumb and single grain; roots and stones as above, sharp boundary to
B″ 10–25 in.	Reddish-brown (5 YR 4/8) sandy light loam, with large patches of greyer and redder hue; slight cementation but breaking readily to crumb; more stones than above; pebbles leave imprint in which there is a thin halo of reddish clay; flecks of Mn/Fe; some live tree roots, many dead roots; merging boundary to
B″/C 25–32 in.	Reddish (3·75 YR 4/4) sandy medium loam; very stony with pebbles aureoled with clay; rather compact horizon.

The micro-podzol lies above a pale yellow-brown horizon (A'_e) with bleached sand grains embedded in the fabric, suggesting that the leaching and weathering which has been intense in the confined zone beneath the humus layers has begun to affect the horizon below. Based on morphology, the upper phase of soil development (A'_e and B′) suggests very weak podzolization, though there is little evidence to confirm this in the analytical data (S. Pk. 13, Fig. 2 and Table 1). Moreover, the composition of the colloid fraction shows little variation, apart from slight eluviation of alumina, and thus conforms with the characteristics for brown earths as detailed by Robinson (1949, p. 319).

The lower phase of development of these soils gives some clue to past pedological processes, for the amount of clay increases with depth until at approximately 30 in. there is a compact stony layer, with clay films surrounding the stones. The compactness has restricted percolation which is reflected in the patches of grey-brown loam developed in the horizon above, which seem to have been induced through gleying. The evidence of clay films and compaction suggests clay translocation possibly indicating the process which initiates soil degradation in these more loamy soils, leading ultimately to podzolization.

A pollen analysis of a representative site in the open woodland revealed that the present vegetation structure is, to a first approximation, a continuation of past conditions (Fig. 3, S. Pk. 13). The high bracken pollen count in the upper layers reflects the present dominance of this species on the site. Though there have been vegetation changes there is no evidence of dense high forest, and throughout the profile light-demanding species occur. The importance of birch in association with grasses, bracken, Ericaceae, and oak, indicates fairly open woodland with a moderately well-developed ground flora.

(*c*) *Soils associated with Calluna heath*

Areas of Calluna heath, with *Ulex* sp., *Deschampsia flexuosa*, and *Molinia caerulea* occur throughout the park. The heaths are generally stabilized by periodic accidental fires, though in some areas owing to preferential advantage after fires, bracken has successfully advanced on to the heath, suppressing the *Calluna*, which in turn has been colonized by sub-spontaneous birch.

The soils under dry sandy heaths in lowland Britain and west and north Europe are widely found to be humus–iron podzols (Robinson, 1949; Kubiena, 1953), that is, they are soils with clearly developed illuvial organic and iron horizons. Much has been written about these soils, so that detailed general considerations may not be necessary, though a description of a typical British profile may be valuable (S. Pk. 2, no. 4 of Fig. 1).

L ¼ in.	Calluna litter held together by mosses, grass, and Calluna roots.
F ½ in.	Brown, slightly rust coloured; Calluna remains.
H/A_e 0–4 in.	Black, more compact than the F layer, embedded with numerous bleached sand grains. Roots strongly developed.
A_e 4–8 in.	Pinkish-grey (5 YR 3/2) sand; numerous round quartzite pebbles (¼–10 in. diam.); few fine roots; structureless, sharp boundary to
B_h 8–9½ in.	Black humic sand with bleached grains; stony; few roots; slightly cemented though easily breaking to crumb; merging boundary to
$B_{h/e}$ 9½–18 in.	Brown (5 YR 2/2) friable loamy sand; very stony; slightly cemented, no visible pores; merging boundary to
B_s 18–25 in.	Orange-brown (5 YR 3/6) sand; very stony; slightly cemented though breaking easily to crumb; fine pores.
C > 25 in.	Orange (5 YR 4/6) sand; slightly cemented, breaking to single grain with pressure; no roots.

The humus horizons have developed under acid, base-deficient conditions with good aeration particularly in the L/F horizon, though this

is vestigial owing to burning. The H/A_e horizon, too, shows in its morphology the consequential results of periodic fires, for after depletion of the humus layers by burning the residue is intermixed with bleached sand grains eroded from soils in which mineral horizons have been exposed. The fauna consists mainly of mites and the horizons in total correspond to raw humus (Kubiena, 1953).

The bleached structureless A_e horizon has a low colloidal organic-matter content but overlies a black highly organic, slightly cemented B, which with moderate pressure breaks to crumbs. The amount of free iron oxide in the B_h horizon of these soils varies considerably, but invariably a higher percentage is associated with organic matter than in the iron-rich B_s horizon beneath it (Table 2). The mechanical eluviation of clay is normal in these soils (Robinson, 1949, p. 313), though the differentiation of the silica and sesquioxides in the clay fraction (Table 3) indicated by its variable composition implies strong chemical decomposition also.

The morphology and analytical data for the iron podzol suggested that translocation of iron and the production of a strongly bleached A_e horizon was followed by the deposition of colloidal organic matter at the A_e/B_s junction. Evidence, in well developed humus–iron podzols, of an earlier mature iron-podzol stage is difficult to prove, but of five profiles (S. Pk. 2, 5, 8, 9, 10, Tables 1 and 2) one from a heath site (S. Pk. 5) and one from a woodland site (S. Pk. 8) produced evidence which conflicts with the idea of a preceding mature iron-podzol stage.

Samples from the horizons of these five profiles were gently warmed in H_2O_2 until all the organic matter was oxidized. A comparison of the resulting soil colours showed that the B_h horizons of S. Pk. 2, 9, and 10 were completely bleached, whereas in the case of S. Pk. 5 and 8 there was a brownish residue indicating the presence of a considerable amount of non-organically combined iron. These general statements are corroborated by the free iron data (Tables 1 and 2). This suggests that the production of a completely bleached A_e horizon is not a necessary precursor to the formation of an organic B horizon within it (Table 2). It is probable, therefore, that humus–iron podzols can develop from podzol intergrades if woodland is replaced by heath, before soil degradation has reached the mature iron-podzol stage.

Discussion

The sandy brown earths apart, the soils described are formed from similar though not identical parent materials, and as factors other than vegetation are effectively constant they form a sequence of different development stages, each stage being determined by the influence of present and past vegetation. The sequence podzol intergrade—iron podzol—humus–iron podzol is seen in this geographically restricted area only because, on coarse-textured parent materials, apparently slight environmental changes are reflected in significant alterations in soil morphology.

The sandy brown earths with relic *sol lessivé* features seem to have resisted podzolization possibly through the influence of a higher percentage

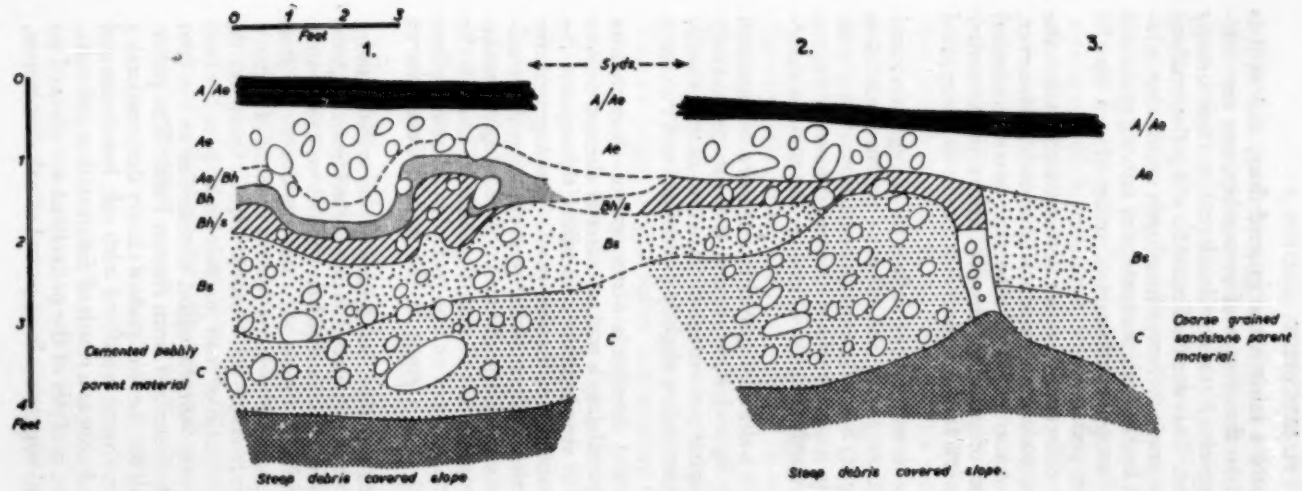
of colloidal particles throughout the profile. However, the phase of clay eluviation and consequent impoverishment in bases has been followed by the development of strongly acid mor humus, so that edaphic factors have now been modified to favour podzolization. Duchaufour (1956*a*, p. 193) describing soil development on sandy parent materials states that clay illuviation is a characteristic process of Atlantic oakwoods and that though well-grown climax oakwood is associated with *sol lessivé*, the more open oakwood with acidophilous ground flora is characterized by *sol lessivé faiblement podzolique*, or even *sol podzolique*.

Since clay illuviation forms a stage in the process of degradation towards podzols (Duchaufour, 1956*a*, p. 193; Scheys *et al.*, 1954), sandy brown earths, which in natural environments appear to correspond closely with *sol lessivé faiblement podzolique*, may be regarded as the youngest stage in a maturity sequence, sandy brown earth—podzol intergrade—iron podzol—humus-iron podzol. Evidence is not available from all sites of clay movement preceding podzolization and in highly permeable sands podzolization may well have been an initial soil formation process.

Though the effect of a slightly finer-textured parent material may account for the geographic association of sandy brown earths and podzols, ecological differences and consequent differences in micro-climate also are likely to influence the speed of profile development.

Distinct local variation in profile morphology is typical of woodland soils on sandy parent materials. The interception of rainfall by the woodland canopy results in an uneven distribution (Ovington, 1954) so that patches of more and less leached soils occur; furthermore, differences in the kind of surface organic horizons related to the accumulation of specific litter also affect profile development. Though it is tempting to suggest that present differences in vegetation and micro-climate possibly determine the extent of profile development, it should be remembered that soil profiles result from the cumulative effects of varying ecological conditions over many centuries. Studies of soils related to the present vegetation, therefore, may not decisively demonstrate the effects of vegetation on soil formation. In Sutton Park and Sherwood Forest (Nottinghamshire) slightly podzolized sandy brown earths are associated with open canopy oakwood yet in similar heathy, open canopy oakwoods of the Ercall (Shropshire) podzols occur on granophyre and rhyolite, parent materials less likely to give rise to podzols than quartz-rich sands. Obviously past and present ecological conditions determine the extent of profile development and thus the influence in soil formation of a particular plant species must remain obscure in the absence of data on site history.

The pollen counts from profiles in Sutton Park allow some conclusions to be drawn. The dominance of oak pollen to 18 in. in the iron podzol (Fig. 3, S. Pk. 11) with little pollen that could be derived from a ground flora suggests a long, though indefinable, period of dense oak forest, and in this environment the podzolizing influence of oakwood is clear. The podzol intergrade (Fig. 3, S. Pk. 7) occurs in what was probably coppiced woodland when the park was given to Sutton Coldfield in 1528.



Hor.	(a) % Fe_2O_3	(b) % Fe_2O_3	(c) O.M.
A/Ae	0·4	0·3	6·9
Ae	0·5	0·4	3·5
Bh	2·1	1·2	15·7
Bh/s	2·0	1·6	8·7
Bs	1·2	1·2	0·7
C	1·0	0·9	0·7

Hor.	(a) % Fe_2O_3	(b) % Fe_2O_3	(c) O.M.
Ae	0·8	0·4	2·9
Bh/s	1·5	1·5	2·3
Bs	0·7	0·8	0·9
C	0·7	0·8	0·5

Hor.	(a) % Fe_2O_3	(b) % Fe_2O_3	(c) O.M.
A/Ae			10·2
Ae	0·8	0·5	3·0
Bs	1·0	0·8	1·5
C	0·9	0·8	0·2

(a) % Fe_2O_3 (modified Deb).
(b) % Fe_2O_3 (modified Deb preceded by H_2O_2 treatment).
(c) Colloidal O.M. expressed as Spekker units.

FIG. 4

Regular cutting would ensure a fairly virile ground flora, and as it is likely that coppicing ceased on the change of ownership, one may estimate that the podzol intergrades have not developed in close canopy woodland for many centuries. This was confirmed by the pollen analysis (Fig. 3), for this showed the gradual change from open conditions (presumably coppice), indicated by the high percentage of ericoid, grass and weed pollen, to the close canopy conditions of today shown by the dominance of tree and shrub pollen.

It is possible that these differences in site history account for the profile development of iron podzol and podzol intergrade. However, since there is no evidence of the length of time the present ecological conditions have operated or of possible site differences much earlier than the present vegetation cycle the hypothesis needs to be applied with care.

Though there is evidence to suggest the influence of vegetation and micro-climate in soil formation, locally the effect of parent material is apparent. The diagram (Fig. 4) is a schematic presentation of an almost continuous section exposed in a quarry where the parent material on one side is extremely stony and partly indurated, and on the other a stoneless coarse sandstone.

The soil developed on the indurated gravel is a mature humus-iron podzol with well developed B_h and B_s horizons; this merges laterally into an iron podzol, with a higher percentage of fine earth in the gravelly parent material and this in turn into a slightly podzolized soil on coarse sandstone.

The soil sequence of podzol intergrade—iron podzol—humus–iron podzol, though in this case paralleling a parent material change, follows the general trend of horizon development described throughout the park. Parent material undoubtedly influences profile development, for in local areas of base-deficient pebbly material podzolization is intensified. However, this does not change the direction of pedological evolution but only hastens the progress to soil maturity, that is, towards the humus–iron podzol. The occurrence of an iron podzol in an intermediate position again indicates that it is a stage in the podzol development sequence.

The developmental sequence podzol intergrade—iron podzol, under deciduous woodland shows the same trend that is reported from Belgium by Munault (1959). Two soils are described developed on sandy substrates originally under deciduous forest with oak dominant; an iron podzol, with well formed A_e and B_s horizons but no horizon of organic accumulation, and a less podzolized soil with a slightly purplish A_e which is stated to be 'characteristic of iron podzols under broad-leaved trees'. These soils show strong morphological similarities to the iron podzol and podzol intergrade described from Sutton Park. The pollen spectra presented by Munault for the iron podzol clearly demonstrates a change of vegetation from deciduous woodland with oak, hornbeam and hazel dominant, to heath, probably as a result of deforestation and cultivation. In contrast, the pollen analysis of the podzolized soil showed no definite human influence, and suggests a long period of oak dominance,

initiated in open canopy conditions as evidenced by the high percentage of ferns, grasses, and ericaceous species in the lowest soil layers. It is interesting to note that the site-vegetation histories as related to the formation of the iron podzols described from Sutton Park and by Munault differ. In the one case an apparently uninterrupted sequence of oak forest has produced an iron podzol, and in the other the podzol results from superimposition of strong anthropogenic influences on the course of soil development, which was initiated under generally similar ecological conditions to those of Sutton Park.

In a study of soil development on sandy deposits in Hageland, Belgium, Scheys *et al.* (1954) present strong evidence to indicate that the iron podzol is a deciduous forest phase, and that subsequently, with a vegetation change to heath, an organic B horizon is formed at the junction of the A_e and B_s horizons. This same succession of B horizon development is referred to also by Duchaufour (1956*a*) though in this case in connexion with heaths, and again by Burges and Drover (1953) in a study of a time sequence of beach deposits in New South Wales.

The possible historical relationship of such woodland soils to heathland soils presents some difficulty, though circumstantial evidence invites the suggestion that following a period of soil degradation under woodland, mature humus–iron podzols have developed in association with heath, introduced through grazing, burning, and felling. However, in none of the heath sites examined on the woodland fringe was there any irrefutable evidence of previous podzolization under woodland, though Tansley (1953, p. 354) states that existing heaths often occupy the sites of destroyed or degenerate woodland.

Heath areas are themselves being altered through the preferential advantage which *Pteridium* obtains over *Calluna* after fire. *Pteridium* in this way prepares a favourable loose humus layer for the regeneration of birch, though the vegetation change, admittedly without a grassland phase, does not result in the profile regeneration seen in north-east Yorkshire (Dimbleby, 1952).

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SOME SARAWAK SOILS

I. SOILS OF THE REGION CENTRED ON THE USUN APAU PLATEAUX

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(WITH ONE PLATE)

Summary

Most of the landscape in central Borneo is sub-mature and undergoing active degradation by creep and surface wash. The prevalent acid yellow soils, therefore, show only limited horizon differentiation. Limited areas of almost flat juvenile relief, arising from volcanic activity subsequent to the onset of the downcutting of the country rock, give rise to characteristic hydromorphic soils and vegetation.

Under the extreme leaching processes operating in the moss forest zone at 4,330 ft. above sea-level a tonalite porphyry gives rise to substantial amounts of gibbsite on weathering.

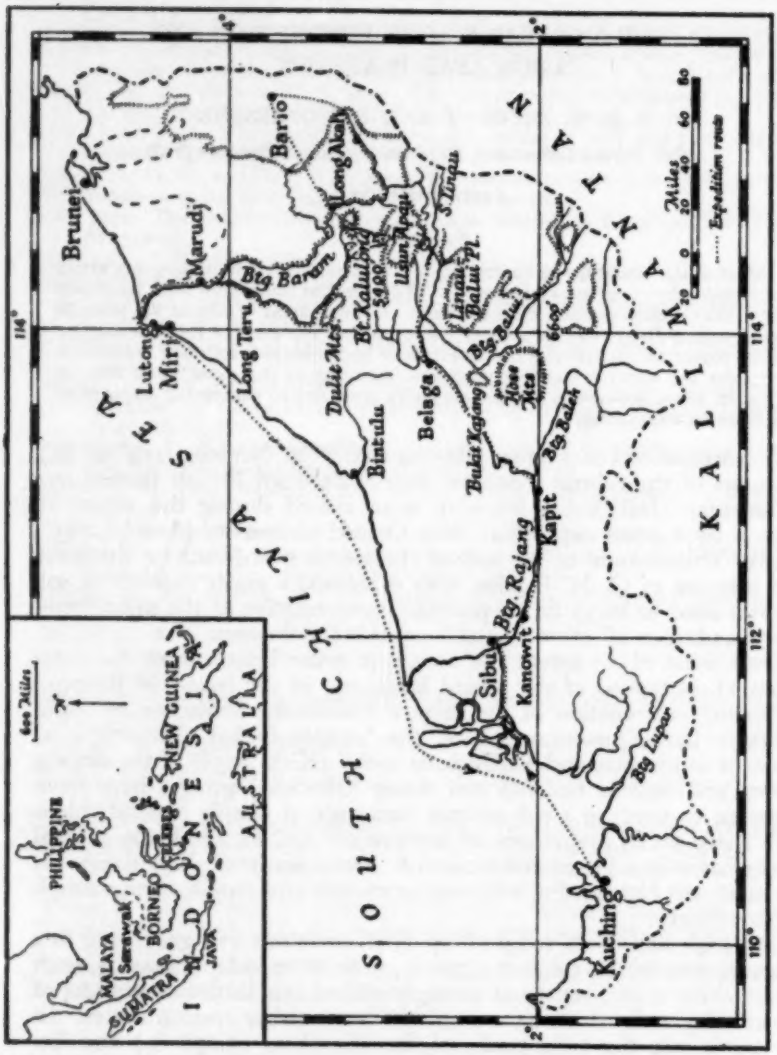
THE inaccessible Usun Apau plateaux (lat. 2° 50′ N.; long. 114° 40′ E.), offshoots of the central mountain barrier between British Borneo and Kalimantan (Indonesian Borneo), were visited during the winter of 1955–6 by a small expedition from Oxford University (Arnold, 1957, 1958). This account of the soils of the area is based both on the notes and samples of G. H. Pickles, who examined a small number of soil profiles sited to be as far as possible representative of the main forest types, and upon all other available records for the area.

Over most of its extent the area, 120 miles inland from the coast (Map 1), is typical of the inland landscape of the island of Borneo.[1] Following rejuvenation of the mature Pleistocene landscape by rapid uplift in later Quaternary times, the 'steeply folded alternations of resistant sandstones and argillaceous rocks' (Kirk, 1958) of the Rajang (lower and middle Eocene) and Setap (Miocene) groups have been dissected to produce a sub-mature landscape of deeply divided ridges with sharp crests and slopes of perhaps 20°–30° in which the general level of crestlines lies at about 2,000 ft. above sea-level. The rivers, for the most part fast-flowing with numerous falls and rapids, form a rough trellis pattern.

The high Batu Bora range (Map 2) of sandstone and grit rising to a towering precipitous ridge at 4,700 ft., with other isolated massifs, such as the Dulit range, represent strongly etched synclinal monadnocks of the country rock which have persisted from earlier erosion cycles. In the north-east the twin peaks of Bt.[2] Kalulong (5,158 ft.) and Bt. Seludong (4,500 ft.) result from the uncovering of a tonalite-porphyry intrusion.

[1] For the geology of the area see Campbell (1956), Kirk (1958), Mohr (1944), Roe (1954), and Whittle (1953).

[2] Bukit (Bt.) = mountain or peak; Sungai (S.) = river.



MAP 1

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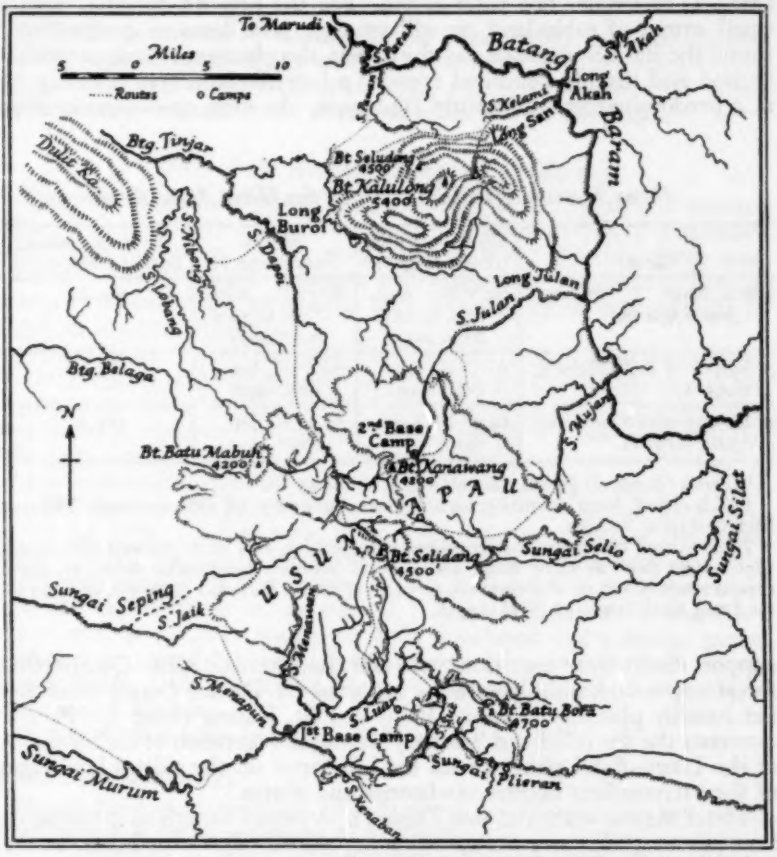
The two plateaux of Usun Apau, about 350 sq. miles in extent, derive from volcanic activity subsequent to the onset of the present cycle of erosion of the ridge landscape. The peaks of Bt. Selidang (4,500 ft.), Bt. Kanawang (4,256 ft.), and Bt. Batu Mabun (4,116 ft.) represent the



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MAP 2

intrusive necks of three volcanoes. To the east and west deep deposits of compact hypersthene dacite tuff are superimposed upon the pre-existing dissected relief, to form level or gently undulating surfaces, respectively 3,200 ft. and 2,500 ft. above sea-level. The surface of the eastern table-land, the only one visited by the expedition, consists of weathered tuff with occasional sand ridges and thick white clay deposits. It is lightly incised by placid streams, which plunge over the margin in high cataracts and falls, to the level of the ridge landscape 800 ft. below.

Undercutting of the softer underlying tuff and sedimentary formations has led to the formation of precipitous escarpments. Appreciable embayment has already occurred. Presumably, as gorges converge, the plateaux will ultimately come to resemble the rugged Hose mountains (Map 1) of similar but older origin. For the present, together with a small extent of table-land on still younger lava flows of quartz-basalt round the Batu Bora range and the S. Sut, the plateaux remain as weakly incised and sharply delimited areas of a juvenile landform standing up in a predominantly sub-mature landscape. As such, the volcanic areas

TABLE 1

Some Meteorological Records for the Usun Apau Area

Camps	*Usun Apau area (mean temp.*)*	*Bintulu (mean temp.†)*	*Estimated mean‡ annual precipitation*
1 & 2. Near S. Plieran, 1,700–1,900 ft.	74·7° F., mid-Sep. to mid-Nov. 1955	81·1° F., mid-Sep. to mid-Nov. 1955	265 in.
3. Slopes of Bt. Kalulong, 2,255 ft.	65·5° F., late Feb. 1956	79·2° F., late Feb. 1956	260 in.
4. Eastern plateau of Usun Apau, 3,130 ft.	64·7° F., Jan. 1956	79·3° F., Jan. 1956	265 in.

* From Campbell (1956); diurnal range about 15° F.

† Calculated from monthly means from Summary of Observations, Malayan Meteorological Service.

‡ Calculated by comparing measured precipitation over short periods (Campbell, 1956), with those at Long Akah and Bintulu between comparable dates; cf. mean annual totals of 143 in. at Belaga (1949–54), 151 in. for Bintulu (1949–55), and 234 in. for Long Akah (1951–5) (Seal, 1959).

support distinctive vegetation types and characteristic soils. Comparable forest types and soils have been reported by Dames (1958) from the flat basaltic plateaux of Linau-Balui and Bt. Kajang (Map 1). Plate I contrasts the flat relief and 'feathery' *kerangas* vegetation of the volcanics of the Linau-Balui plateau with the hill forest on the ridged landscape of the surrounding Eocene sandstones and shales.

The climate is warm and wet (Table 1). Seasonal variations in temperature (about 3° F.) and precipitation are slight. The expedition, in the field during the wettest six months of the year, experienced rain on 91 out of the 99 days for which records were kept. Rain was heavy and often torrential, leading to flash floods, but was more prolonged and less intense on the plateaux than below. Cloud and drizzle were nearly continuous in the mist belt of the moss forest round the peaks. At all altitudes the relative humidity reached 96–100 per cent. during the night, decreasing to about 90 per cent. under hill forest as the temperature reached its daily maximum shortly after midday.

The Upper Baram and Tinjar rivers and their tributaries are at present occupied by a small number of 'long house' settlements, surrounded by areas of cultivated hill rice and other crops, and dense growths of

secondary-forest fallow. Long-house ruins confirm the former occupation of lands along the Plieran uncultivated since the great Iban raid in the 1880's (Arnold, 1956). The soils of the Plieran Valley are said to be productive: their inaccessibility is the main bar to resettlement. The plateau is uninhabited.

With the exception of cultivated and fallow lands, and the *kerapak* and *kerangas* forest of the juvenile volcanic areas, primary hill forest or submontane rain forest (Richards, 1952, pp. 347–57) covers the whole landscape up to about 4,000 ft. Moss forest covers the peaks.

Soils of the Actively Degrading Landscape

Primary evergreen hill forest is characteristic of sloping or well-drained sites up to about 4,000 ft. It is dominated by large-leaved buttressed trees, with an upper canopy at 90–100 ft. but with some large trees reaching 150 ft. *Liana* creepers are common. The forest floor is occupied mainly by regenerating tree species, not usually sufficiently dense to impede movement.

The soils on the interfluvial ridges and the steeper slopes round the table-land and on the three peaks above it are monotonously uniform in appearance. They are yellow (10 YR-2·5 Y) sandy loam to clay soils, 2–4 ft. deep, commonly sticky and plastic when wet and with more or less grey and rust mottling in the paler subsoil. Even on the steeper slopes percolating ground-water was usually found at a depth of 30–60 in. The depth to the pale horizons decreases towards the valley bottoms, while the better drained soils, often sandy, on the crests of the ridges show warmer colours in the subsoil. Except that more prolonged wet conditions appear to have caused a less well-marked development of rust and red mottling in the subsoil, the soils described for the Usun Apau area appear to be similar to those developed under similar parent materials in mixed lowland Dipterocarp forest up to 1,500 ft. on the slopes of Mt. Dulit (Richards, 1936) and on sloping sites in the coastal areas round Bintulu.

Three profiles were recorded by Pickles:

Profile 1 (i) (No samples)

On soft Miocene (?) sandstone 1,850 ft. above sea-level on a steep slope facing north, near S. Kenabau, a tributary of S. Plieran.

1½–0″ Litter layer containing many live roots.

0–1″ Dark sandy loam, with numerous fine roots; few fine roots below this horizon.

1–60″ Yellow sandy clay loam, grading into sandy clay at depth; few roots below 8 in.; some grey mottling at 18 in., increasing in extent until at 42 in. grey becomes the dominant colour; rust coloured concretions from 42 in.; fragments of rotting sandstone increase in frequency from 36 in.

Profile 4 (i)

On shales and sandstone, with fallen rocks of tonalite and hornfels, 2,255 ft. above sea-level on a steep slope at the foot of the north face of the peak of Bt. Kalulong.

½–0″ Leaves and decomposing litter.

0–51″ Yellow (10 YR 8/6) sandy clay with a few faint orange and grey mottles;

structureless; sticky and plastic when wet, friable when moist, hard when dry; some tonalite fragments present.

51"+ Grey-brown (2·5 Y 5/2) soft shaly silty clay with a few fine distinct yellowish red mottles; fairly sticky and fairly plastic when wet, hard when dry; on drying breaks into fine angular blocky lumps with pale surfaces. Water-table at 61 in.

Many fine roots in top 1½ in.; large roots down to 5½ in.; some fine roots down to 51 in.

Profile 4 (ii)

As for 4 (i), but at 3,300 ft. above sea-level.

½–0" Leaves and decomposing litter.

0–2" Light brown-grey (2·5 Y 6/2) coarse sandy loam containing frequent fragments of biotite and quartz up to 4 mm. in diameter, with incorporated humus and much undecomposed organic matter; non-sticky, non-plastic when wet; slightly hard to hard when dry; moderate fine sub-angular blocky structure developed on drying.

2–34" Pale yellow (2·5 Y 9/4) coarse sandy clay loam with infrequent small orange and grey fragments, and frequent quartz grains up to 5 mm.; structureless; slightly sticky and plastic when wet, fairly hard when dry; no discernible organic matter. Water-table at 20 in.

34–51" White (5 Y 9/1) coarse sandy clay loam with common fine distinct reddish yellow (7·5 YR 6/8) mottling, especially round root channels; frequent quartz and biotite grains up to 2·5 mm.; structureless.

There are many large and fine roots at 51 in.

The results of analyses are given in Tables 2 and 3.

In their relative lack of textural horizons and indeed in any sharp variations down the profile, the Usun Apau soils, in so far as this small number of descriptions is representative, may be said to reflect the state of dynamic equilibrium existing in a landscape undergoing rapid degradation. On the steep slopes surface wash initiated by heavy raindrops falling from leaves and branches, and soil creep, serve to rejuvenate the soils continuously and to maintain their profiles in a steady state of suspended development.

The occurrence of soil profiles on tonalite-porphyry and on the dacite ridges on the Usun Apau plateau itself (C. J. Campbell (priv. comm.), Kirk, 1958), apparently similar to those on the interfluvial sandstone and shale ridges, is paralleled by similar profiles at 4,400 ft. on the dacite tuff of the Hose mountains (Kirk, 1958) and on andesite tuffs in Java (van Schuylenborgh, 1958), also by 'pale yellow clay with quartz crystals in it' on the dacites and rhyolites of the Müller mountains between East and West Kalimantan (Mohr, 1944, p. 390).

Soils under moss forest

Profile 4 (iii) lies in a low moss forest 620 ft. below the lower crest of Bt. Kalulong. On an average the lower boundary of moss forest lies at 4,000–4,500 ft., though on exposed sites such as the southern spurs of the plateaux and on the Batu Bora ridge it extends down to 2,500 ft. and in other places, for example on the peak of Bt. Selidang, rain forest extended up to over 5,000 ft. Moss forest consists typically of gnarled and stunted trees not more than 10–15 ft. high with numerous branches

TABLE 2

Chemical Data for Soil Profiles

Profile	4 (i) (2,255 ft.)		4 (ii) (3,300 ft.)			4 (iii) (4,330 ft.)			3 (ii) (3,170 ft.)			
Depth (in.)	0–25	51	0–2	18–20	34–51	0–8	8–13	25	1–3	18	42	
OM %	1·9	1·4	11·2	1·8	1·5	82·8	13·9	5·1	34·4	7·5	0·3	As % on fine earth
N %	0·13	0·13	0·38	0·06	0·05	2·01	0·38	0·18	1·05	0·18	0·02	
C/N	8·4	6·1	16·9	16·7	18·6	23·9	21·2	16·4	19·1	24·5	12·5	
pH	4·23	2·70	4·16	4·22	4·27	2·94	4·02	4·96	3·58	3·98	4·22	In M/100 $CaCl_2$
Exch. H	7·2	13·6	•	3·2	4·1	•	7·3	0·7	•	3·3	4·3	As m.e./100 g. fine earth
,, Ca	0·6	0·4	1·9	0·2	0·3	•	0·7	0·2	•	0·2	0·06	
,, Mg	1·7	3·7	3·3	1·1	1·1	•	..	0·9	•	1·0	0·7	
,, K	0·4	0·3	0·8	0·2	0·3	•	0·6	0·2	•	0·2	0·2	
Total analyses												
Quartz	23	20	•	41	30	•	48	14·8	•	(66)†	(46)†	% on ignited fine earth
Combined silica	44	49	•	35	38	•	22	36	•	(10)	(9)	
Qu/C.S.	0·52	0·41	•	1·17	0·79	•	2·18	0·41	•	(6·6)	(5·1)	
Al_2O_3	17	21	•	18	22	•	18	24	•	24	32	
$Fe_2O_3 + TiO_2$	7·9	16	•	6	5·4	•	6·1	4·4	•	4·5	6·0	
CaO	0·23	0·23	•	0·45	0·35	•	1·12	0·63	•	0·18	0·35	
MgO	0·56	0·90	•	0·69	1·02	•	1·07	1·08	•	0·51	0·63	
K_2O	0·88	3·84	•	0·89	1·35	•	1·31	1·15	•	0·11	0·69	

• Insufficient sample.

† Total Silica analyses are believed to be reliable, but Quartz analyses proved to be difficult. Results of the latter and the derived figures for Combined Silica may be in error.

Organic matter by Walkley and Black (×1·33 recovery factor); Exchangeable H by titration of M $CaCl_2$ leachate; Total analyses, including SiO_2, by fusion with Na_2CO_3; Fe and Ti separated with cupferron; Quartz determined by tri-acid method (Hardy, Follett-Smith, 1931) and Combined Silica by difference.

TABLE 3

Clay Mineral Analyses

Profile	*Depth*	
4 (i)	0–25″	90% mica; 10% kaolin; traces vermiculite, lepidocrocite, goethite, quartz
	51″	95% mica; 5% kaolin; traces lepidocrocite, goethite, quartz.
4 (ii)	18–20″ 34–51″	75% kaolin; 25% mica; traces vermiculite, gibbsite, quartz — Trace chlorite; Trace lepidocrocite
4 (iii)	8–13″	45% kaolin; 35% vermiculite; 20% gibbsite, trace of quartz
	25″	Largely gibbsite; trace of kaolin and quartz — Very little clay in these samples
3 (ii)	18″ 42″	Largely kaolin (mainly meta-halloysite) with traces of gibbsite and quartz, and (at 42″) significant amounts of felspar.

and small tough leaves. Moss and epiphytes cover the branches. Movement is impeded by fallen trees, exposed boulders, and densely intertwined aerial roots, all covered by about 6 in. of dense, wet moss.

Profile 4 (iii)

On tonalite porphyry at 4,330 ft., just below the crest of Bt. Kalulong.

0–8″ Dark reddish-brown (5 YR 2/2) slightly fibrous peat, very hard when dry, containing a few bleached fragments of rotting parent material.

8–13″ Weak red (2·5 YR 4/2) coarse sand with frequent small fragments of biotite and quartz; small medium sub-angular blocky aggregates, with weak

brown humus-stained surfaces and yellow to pale yellow matrix; very friable when moist, slightly hard when dry.

13–40″ Very pale reddish-brown (2·5 YR 7/4) micaceous medium to coarse sandy loam, with frequent particles of biotite and quartz, and fragments of rotting tonalite.

Most of the roots are confined to the top 8 in. of the profile, but both large and small roots occur down to the bottom of the pit.

The results of analyses are given in Tables 2 and 3. The very significant amounts of gibbsite in the small clay fraction (Du Feu, 1958), resulting from the weathering of a tonalite-porphyry containing more than 20 per

TABLE 4

Mineralogical Analyses of Profile 4 (iii)

Fraction analysed	*Light separate*	*Heavy separate*
0–8″ all sizes; no separation	Quartz, andesine, weathered biotite, opal phytoliths (very common) with some opaques, zircon, and hornblende.	
8–13″ > 300-mesh	Andesine*, quartz and weathered biotite (hydrobiotite and/or vermiculite); minor amounts of orthoclase and a few opal phytoliths.	(< 1%) — opaques, zircon, green and brown hornblende, sillimanite, greyish fibrous amphibole (or enstatite), biotite, and garnet.
13–25″ 50–300-mesh	As above; opal phytoliths in minor amounts	As above

* Andesine grains very clear, and with little decomposition products, but usually exhibit highly corroded edges.

cent. quartz (Campbell, 1956), suggest a high intensity for the weathering process. The formation of gibbsite as a result of the weathering of an acidic parent material is paralleled by a similar report (Barshad, Rojas-Cruz, 1950) for H. Jenny's (1948) Giant Podzol from Colombia (8,070 ft.), weathered from dacite tuff. In the case of the Colombian soil the authors admit the possibility that the parent material itself may contain free alumina. In both soils the gibbsite has apparently been partially resilicified in the upper horizons. In the present instance identification of the parent material is in part confirmed by mineralogical analysis (Table 4).

The persistence of substantial amounts of andesine felspar throughout the profile, taken in conjunction with the fairly uniform total K_2O content in this and similar profiles in New Guinea (Hardon, 1936) suggest that the weathering pressure on the primary minerals is in fact less intense than might at first appear. The results of the weathering process are undoubted, for example the notable increase in the 'quartz/combined silica' ratio up the profile, but the persistence of K_2O and felspar would seem to indicate that the formation of gibbsite in the lower horizons is the consequence rather of an intense leaching pressure, removing soluble silica, than of a high intensity of decomposition.

Similar profiles have been reported by Richards (1936) on Mt. Dulit

and by Hardon (1936) on Jurassic shales and quartzite at 6,000 ft. on the Arfak Mts. in NW. New Guinea.

Soils of Areas of Juvenile Relief

Kerapak forest was found on the wet and boggy soils of level outcrops of columnar quartz-basalt lava and also on poorly drained basaltic alluvium. It appears to be a poorly drained member of the group of *kerangas* forest types (Browne, 1952), with many affinities to swamp forest, and is characterized by a small number of species, the red *Selunsor* (*Tristiana elliptica*) being dominant, 20–30 ft. high with no stratification, over an understory containing abundant mosses and insectivorous plants. The trees have a very slow rate of growth and show gnarled trunks and very large stilt roots. There are few climbers. Water draining from the areas of *kerapak* forest is characteristically reddish in colour.

A *kerapak* profile on alluvium, 2 (i), was recorded by Pickles.

Profile 2 (i) (No samples)

On basaltic alluvium at 2,360 ft. about ¼ mile from the basalt escarpment over the S. Sut, south-west of the Batu Bora range.

¼–0″ Live moss.
0–2″ Reddish sandy soil, densely rooted and with much incompletely decomposed organic matter.
2–11″ Saturated grey fine sand, with many live and dead roots, large and small.
11–17″ Saturated whitish grey fine sand; only a few small roots.
17″+ Rotting basalt.

It is unfortunate that a noticeable admixture of quartz sand from the Batu Bora range makes the only profile description available atypical of poorly drained basalt soils. However, G. Whittles (priv. comm.) reports that on an interfluve north of the Batu Bora the flat top of a smaller outlier of columnar vesicular basalt has rotted to a 'white puggy clay'. Soils similar to profile 2 (i) occur on poorly drained sites on the basaltic Linau-Balui and Bt. Kajang plateaux, where the soil parent material has also been modified by the addition of quartzitic material (Dames, 1958). Uncontaminated poorly drained basalt soils on the same plateaux consist of dark grey and olive-grey silty clays. *Kerapak* soil profiles do not appear under any circumstances to be of 'margalitic' type.

Under conditions of good external drainage basalts (Dames, l.c.) weather locally to olive-brown and dark brown silty or loamy clay soils. Mohr (1944, p. 390) describes similar profiles in Kalimantan on diabases of the Danau formation.

The high-level Kerangas *forest* on the dacite tuffs of the plateaux is associated with soils that are rather similar in appearance to those under *kerapak* forest. The main canopy of the forest stands at about 30 ft. with some emergents rising to 60 or 100 ft. *Casuarina* spp. and the *damar* tree—*Agathis* sp. (? *alba*) are dominants. There is much moss on the trunks and wet forest floor, and numerous pitcher plants, but only a few small climbers; the greater part of the lower story is filled by a dense growth of spiny *rotan* which makes movement away from

paths extremely slow. Streams draining from *kerangas* forest show a characteristic 'blackwater' appearance.

Two very similar profiles were recorded beneath *kerangas* forest on the eastern table-land, one of which (profile 3 (ii)) is given here:

Profile 3 (ii)

1½–0″ Decomposing litter.
0–2″ Very dark brown (10 YR 2/2) slightly fibrous peat, containing a small quantity of coarse sand.
2–30″ Grey to light grey (5 Y 6/1) coarse sandy clay loam with a few distinct root channels; structureless; non-sticky and non-plastic when wet, slightly hard when dry; contains appreciable quantities of rotting rock, carbonized roots and partially decomposed fragments of *damar* resin. Water table at 23 in.
30″+ White (5 Y 8/1) very fine sandy clay loam, fine mottled with orange, containing a few coarse quartz fragments; structureless; slightly sticky and slightly plastic.
Live roots down to 5 in.

Tables 2 and 3 give the results of analyses. The pH is surprisingly low.

Clearly the determining factors with regard to both the *kerangas* and the plateau *kerapak* profiles are the poor external drainage and very limited mass-wasting, both being the consequence of a juvenile landform, which under current conditions of climate and available relief might be said to be a relatively ephemeral phenomenon. Similar tuffaceous and basaltic parent materials on well-drained sites give rise to quite different and, for the area, more normal profiles.

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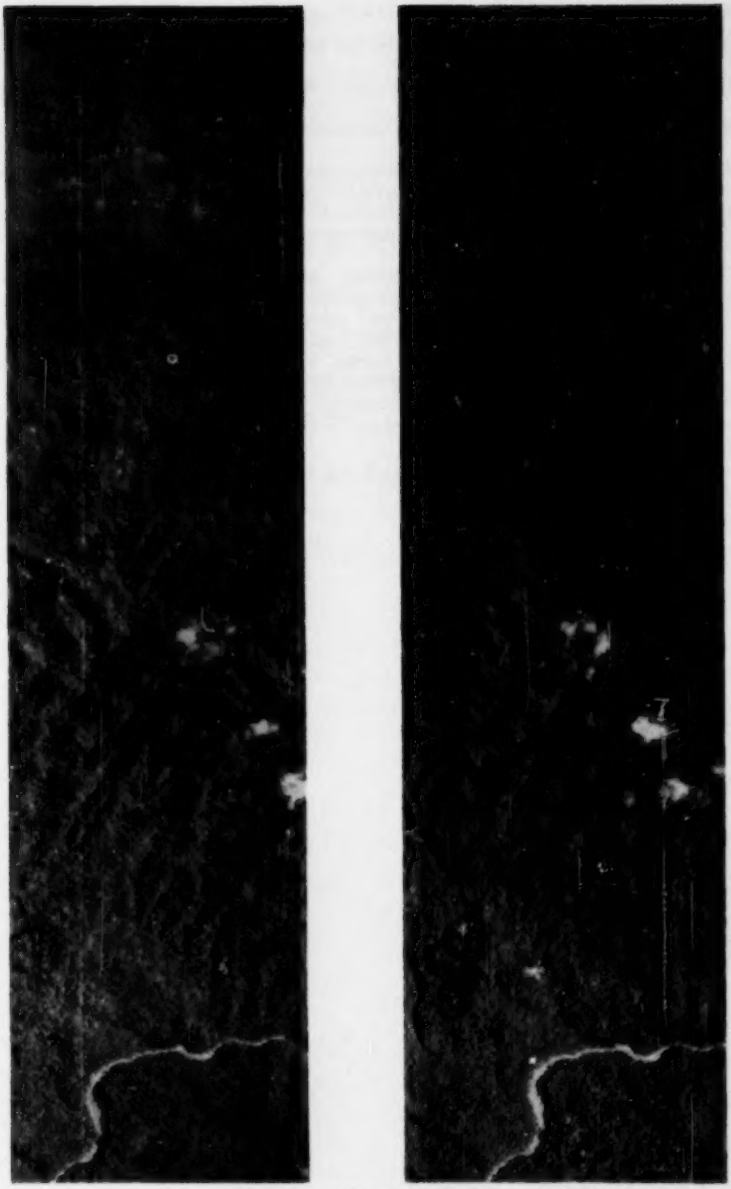

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Stereo-pair of the Linau-Balui plateau (scale approx. 1:30,000) to contrast the *kerangas* vegetation and flat relief of the volcanic formations with the sharply dissected ridged landscape on the Eocene sandstones and shales.

P. H. T. BECKETT *and* D. HOPKINSON—PLATE I

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EVOLUTION OF THE TWO YOUNGEST (QUATERNARY) SOIL LAYERS IN THE SOUTH-EASTERN PORTION OF THE AUSTRALIAN ARID ZONE

I. THE PARAKYLIA LAYER

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Summary

The Parakylia layer consists of a diversity of soils that formed during a former pluvial period. Representative profiles are given.

The soils developed on deposits consisting of a mixture of water- and wind-transported components. The period of erosion-deposition, when the parent material layer formed, was initiated by the onset of arid climatic conditions. The climate eventually became desertic throughout practically the whole region. Calcareous wind-borne materials, derived through deflation of soils farther to the west, were transported into the region where they were mixed with water-transported materials of local origin. The effects of increasing aridity on erosion and deposition are discussed in relation to the evolution of certain characteristics of the parent material layer and hence of the soils. The surface gravel pavements on many of the soils developed before the soils were formed.

Introduction

In an earlier paper (Jessup, 1960*b*) the lateritic soils of the south-eastern portion of arid Australia were discussed. They occur on remnants of an ancient land surface. After the formation of the younger land surface, above which the lateritic plateaux rise, the stony tableland soil layer developed (Jessup, 1960*c*).

This layer was later destroyed by erosion in many areas. Then two younger soil layers, the older of which has been called the Parakylia layer, developed (Jessup, 1960*d*). Two distinct stages were involved in the formation of the Parakylia soil layer. These were an early period of erosion-deposition, when the parent materials were deposited, and a later period when the landscape was stable and the soils were formed. The erosional period followed the onset of arid climatic conditions, while soil formation took place when the climate was humid and erosion was at a minimum (Jessup, 1960*d*).

The purpose of the present paper is to discuss the soils of the Parakylia layer and the origin of the parent materials. Investigations were carried out in two extensive and representative areas in the south-eastern portion of arid Australia (see Fig. 1).

Characteristics of the Soils

A diversity of soils[1] developed in the Parakylia layer as a result of differences in the nature of the parent materials, climatic zonations that

[1] Laboratory analyses of soils discussed in this paper have been presented by Crocker and Skewes (1941), Beadle (1948), Jessup (1951), and Jackson (1958).

existed at the time the soils were formed, and differences in drainage status due to topography. The soils can be classified into three groups on the basis of their profile characteristics. These are:

1. Soils that gradually become finer in texture with depth.
2. Soils that are fine-textured throughout the profile.
3. Soils with marked textural profile differentiation.

All the soils in the three groups belong to the Parakylia layer. This

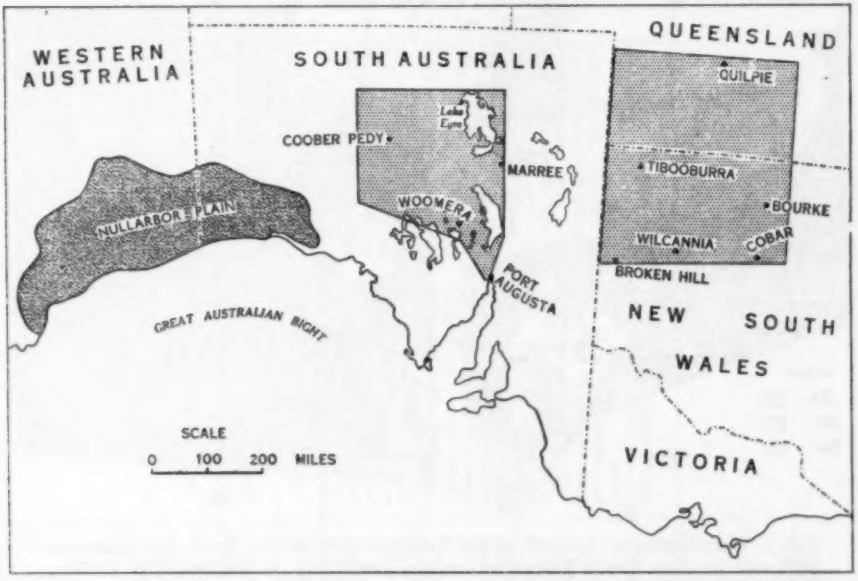

FIG. 1. Showing the location of the two areas studied in relation to the Nullarbor Plain.

is shown by the fact that there is a gradual change in properties between the different soils when the layer is traced in the horizontal plane. Furthermore, the different soils never overlie one another in the vertical plane.

Soils that gradually become finer in texture with depth

Throughout most of the extensive zone in which the Parakylia layer occurs (Fig. 2), the soils in well-drained sites have profiles that are apedal[1] and in which texture gradually becomes finer with depth. Although these features are always exhibited when the soils are examined in the vertical plane, other properties, notably the depth at which carbonate appears in the profiles, are found to vary from one locality to another.

This variation is seen, for example, when the soils are examined along

[1] The term apedal is used for soil that is structureless. Its use avoids the contradiction of stating that the structure of a given soil is 'structureless'.

a traverse from Broken Hill to Cobar. Near Broken Hill (profile 1, Table 1)[1] carbonate appears at a depth of about 13 in. from the soil surface and the upper (non-calcareous) part of the profile has an alkaline reaction. With increasing distance to the east of Broken Hill the depth at which carbonate appears in the profiles gradually and progressively increases. There is a corresponding increase in the acidity of the upper (non-calcareous) horizons (profiles 2, 3, and 4, Table 1). Finally, eastwards from

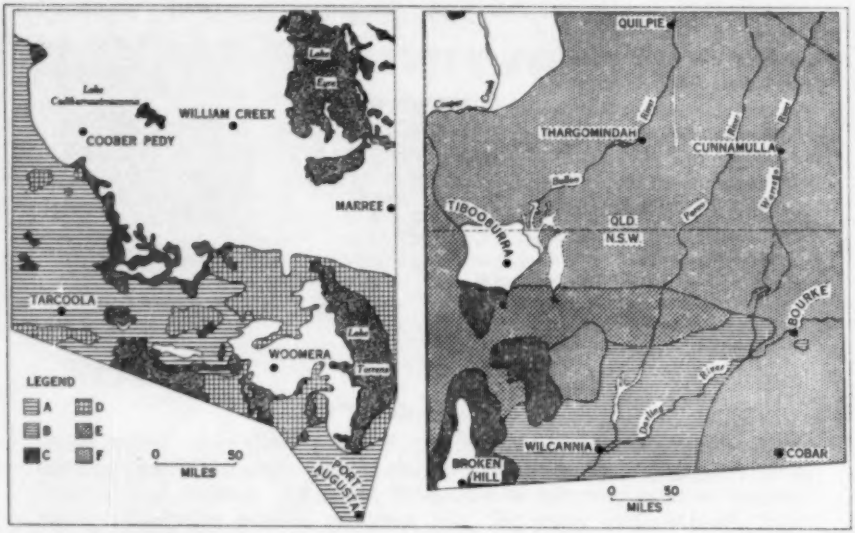

FIG. 2. Distribution of the soils in the Parakylia layer in the South Australian area (*left*) and the New South Wales–Queensland area (*right*). A, mallisols (like profile 1, Table 1); B, mallisols are dominant but grey and brown soils of heavy texture (like profile 2, Table 3) occur in depressions; C, solonetz (like profiles 1 and 2, Table 4); D, desert sandhills (see profiles 1*a* and 1*b*, Table 2) with mallisols between the ridges; E, desert sandhills with mallisols between the ridges, together with minor occurrences of grey and brown soils of heavy texture (like profiles 1 and 2, Table 3) in depressions; F, red earths (like profile 5, Table 1) dominant, but with calcareous red earths (see profile 4, Table 1), brown soils of light texture (profile 3, Table 2) in sand-ridges, and grey and brown soils of heavy texture (like profile 3, Table 3) in depressions.

Cobar, carbonate has been leached to a depth in excess of 4 ft., with the result that the shallower soils are non-calcareous and have an acidic reaction (profile 5, Table 1).

Profile 1 (Table 1) has the characteristics of a mallisol as defined by Northcote (1956). Soils like profile 5 have been called red earths (Jessup, 1960*a*). The term calcareous red earths (Stephens, 1956) has been applied to soils like the red earths except for the presence of carbonate in the lower portion of the profile (profile 4). However, these

[1] All Munsell colour notations in the tables refer to dry soil. Consistence terms follow the system described in the U.S.D.A. Soil Survey Manual, 1951.

TABLE I

Typical Profiles of Soils in the Parakylia Layer that are Characterized by a Gradual Rise in Texture with Depth

Profile 1	*Profile 2*	*Profile 3*	*Profile 4*	*Profile 5*
55 miles east of Broken Hill	*5 miles west of Wilcannia*	*70 miles west of Cobar*	*52 miles west of Cobar*	*20 miles east of Cobar*
0–6″ Apedal, sandy loam, 5 YR 5/8, soft when dry, non-sticky and non-plastic when wet. Diffuse boundary with:	0–4″ Apedal, sandy loam, 5 YR 4/8, soft when dry, non-sticky and non-plastic when wet. Diffuse boundary with:	Trace gravel on surface.	Gravelly surface.	0–6″ Apedal, gritty clay loam, 5 YR 4/6, slightly hard when dry, slightly plastic and non-sticky when wet. Weakly vesicular. Diffuse boundary with:
6–11″ Apedal, sandy clay loam, 2·5 YR 4/6, slightly hard when dry, slightly sticky and slightly plastic when wet. Diffuse with:	4–11″ Apedal, sandy clay loam, 2·5 YR 5/8, slightly hard when dry, slightly sticky and slightly plastic when wet. Diffuse with:	0–8″ Apedal, sandy clay loam, 2·5 YR 4/6, soft when dry, slightly plastic and slightly sticky when wet. Trace gravel. Diffuse boundary with:	0–12″ Apedal, gritty clay loam, 2·5 YR 5/8, slightly hard when dry, slightly plastic and non-sticky when wet. Weakly vesicular; trace gravel. Diffuse boundary with:	6–24″ Apedal, gritty light clay, 2·5 YR 4/6, hard when dry, slightly plastic and non-sticky when wet. Vesicular. Diffuse with:
11–13″ Apedal, sandy clay, 2·5 YR 4/6, slightly hard when dry, slightly sticky and slightly plastic when wet. Diffuse with:	11–16″ Apedal, sandy clay, 2·5 YR 5/8, slightly hard when dry, slightly plastic and slightly sticky when wet. Diffuse with:	8–19″ Apedal, light clay, 2·5 YR 4/8, slightly hard when dry, slightly plastic and slightly sticky when wet. Weakly vesicular; some gravel. Diffuse with:	12–30″ Apedal, gritty light clay, 2·5 YR 5/8, hard when dry, slightly plastic and non-sticky when wet. Weakly vesicular; much gravel. Diffuse with:	24–42″ Apedal, gritty light clay, 2·5 YR 3/6, very hard when dry, slightly plastic and non-sticky when wet. Vesicular.
13–72″ Apedal, sandy clay, 2·5 YR 4/8, hard when dry, slightly sticky and slightly plastic when wet. Very large number of pockets of soft carbonate; some carbonate in fine earth; few carbonate nodules.	16–40″+ Apedal, sandy clay, 2·5 YR 5/6, hard when dry, slightly plastic and slightly sticky when wet. Very large number of pockets of soft carbonate; much carbonate in fine earth; many carbonate nodules.	19–40″+ Apedal, light clay, 5 YR 5/6, very hard when dry, slightly plastic and slightly sticky when wet. Much gravel; much carbonate in fine earth and calcareous coatings on gravel.	30–45″ Apedal, gritty light clay, 2·5 YR 5/8, hard when dry, slightly plastic and non-sticky when wet. Some gravel; moderate amount carbonate in fine earth and some carbonate nodules.	pH: 0–1″, 5·5; 12″, 5·5; 24″, 6·0; 36″, 6·5.
pH: 0–1″, 7·5+.	pH: 0–1″, 7·0; 12″, 7·5+.	pH: 0–1″, 6·5; 12″, 7·0+. Alkaline below.	pH 0–1″, 6·0; 12″, 6·5; 24″, 7·5. Alkaline below.	

subdivisions (mallisol, calcareous red earth, red earth) are arbitrary, since there are all intergrades between mallisols and red earths as can be seen in Table 1.

In many localities the upper portions of the mallisol profiles are missing. These soils suffered widespread and severe erosion during a later erosional period.

Sand-ridges also form part of the Parakylia layer in many localities (Fig. 2). The depth of sand decreases with the distance downslope from the crest. Towards the lower slope of the ridges the sand-ridge profiles

TABLE 2

Typical Profiles of Sand-ridge Soils of the Parakylia Layer

Profile 1	*Profile 2*	*Profile 3*
North of Woomera	*23 miles west of Bourke*	*32 miles north of Bourke*
(a) Crest of high sand-ridge 0–72″+ Sand, 2·5 YR 5/8. (b) Lower sand-ridge 0–48″ Sand, 2·5 YR 5/8. Diffuse boundary with: 48–58″ Apedal, clayey sand, 2·5 YR 4/8, slightly hard when dry, non-sticky and non-plastic when wet. Diffuse with: 58–66″+ Apedal, clayey sand, 2·5 YR 4/8, hard when dry, non-plastic and slightly sticky when wet. Many pockets of soft carbonate. The sand varies in reaction from pH 7·5 to 9·0+.	0–23″ Sand, 2·5 YR 5/8. Diffuse boundary with: 23–48″ Apedal, loamy sand, 2·5 YR 4/8, soft when dry, non-sticky and non-plastic when wet. Diffuse with: 48–60″+ Apedal, loamy sand, 5 YR 5/8, soft when dry, non-plastic and non-sticky when wet. Contains moderate amount of soft carbonate. pH to 3 ft. is 7·0; then becoming alkaline.	0–48″ Sand, 2·5 YR 4/6. Diffuse boundary with: 48–60″ Apedal, clayey sand, 2·5 YR 4/8, hard when dry, non-plastic and non-sticky when wet. Diffuse with: 60–65″+ Apedal, light sandy clay loam, 10 R 3/6, very hard when dry, non-plastic and non-sticky when wet. Vesicular. pH: 5·5 to 6·0 throughout.

merge with those in the inter-ridge areas. Where the soils between the ridges are mallisols, the sand-ridge soils have a weakly to strongly alkaline reaction throughout the profile. Except for those that are superimposed upon the older stony tableland soils (see below), they contain carbonate at depth (profile 1, Table 2). Sand-ridges with these profiles have been called desert sandhills (Stephens, 1956).

Where the inter-ridge soils are red earths, the sand-ridge soils are non-calcareous, acidic in reaction (profile 3, Table 2) and have the characteristics of brown soils of light texture as defined by Prescott (1944). Where the inter-ridge soils are transitional between mallisols and red earths, the sand-ridges may consist of sand (see profile 2, Table 2) that is weakly acidic to neutral in reaction (pH 6·5 to 7·0).

Soils that are fine-textured throughout the profile

Throughout the greater part of its extent, the Parakylia layer occurs on gently undulating plains. There are many small depressions that are basins of local drainage, and here the soil in the layer is quite different from that in the well-drained sites. Representative profiles of depression soils, which are similar in many respects to grey and brown soils of heavy texture as defined by Stephens (1956), are presented in Table 3.

Soils with marked textural profile differentiation

Soils with a sharp boundary between a coarse-textured A horizon and a fine-textured B horizon occur on gently sloping uplands adjacent to low mountain ranges and some plateau remnants. Typical profiles of these (solonetzic) soils are presented in Table 4. Most of them are calcareous below a depth of 10 to 14 in. from the surface (profiles 1 and 2),

TABLE 3

Typical Profiles of Soils that Occur in Low Sites in the Parakylia Layer

Profile 1	*Profile 2*	*Profile 3*
Near Tibooburra	*54 miles south of Thargomindah*	*35 miles north of Bourke*
0–3″ Moderate grade of multi-angular blocky structure with ¼″ peds, clay, 10 YR 7/3, slightly hard when dry, plastic and sticky when wet. Moderate amount of carbonate in fine earth and trace nodular carbonate. Definite boundary with:	0–½″ Weakly laminar, sandy light clay, 2·5 Y 7/2, slightly hard when dry, sticky and plastic when wet. Definite boundary with:	0–½″ Weak grade of multi-angular blocky structure with ¼″ peds, sandy light clay, 10 YR 6/2, slightly hard when dry, slightly plastic and sticky when wet. Definite boundary with:
3–15″ Apedal, clay, predominantly 10 YR 7/3 but with some mottles of 7·5 YR 6/8, hard when dry, plastic and very sticky when wet. Moderate amount of carbonate in fine earth and few small carbonate nodules. Diffuse with:	½–6″ Moderate grade of sub-angular blocky structure with 1½″ peds, sandy clay, 10 YR 6/1, hard when dry, plastic and very sticky when wet. Contains a moderate number of carbonate nodules up to ¼″ in size; no carbonate in fine earth. Diffuse with:	½–27″ Apedal, sandy clay, predominantly 10 YR 7/2 but with some mottles and stainings along fine root channels of 7·5 YR 6/6, hard when dry, slightly plastic and sticky when wet. Very gravelly. Diffuse with:
15–30″ Apedal, clay, colour as above, very hard when dry, plastic and very sticky when wet. Moderate amount of carbonate in fine earth; large amount of micro-crystalline gypsum.	6–72″+ Apedal, sandy clay, 2·5 Y 6/2, very hard when dry, plastic and very sticky when wet. Carbonate as above.	27–42″ Apedal, sandy clay, mottled in 10 YR 6/3 and 7·5 YR 5/4, very hard when dry, plastic and sticky when wet. Some gravel. Diffuse with:
pH: alkaline throughout.	pH: alkaline throughout.	42–54″+ As above but with a few pockets of soft carbonate; no carbonate in fine earth.
		pH 6·0 to 30 in., below which becomes alkaline.

but north-east of Tibooburra there are small occurrences of soils (see profile 3) in which carbonate is absent from the upper 2 ft. of the profile.

In many localities the A horizon of the solonetzic soils is missing. Like the mallisols, they were eroded by wind during a later erosional period.

The Origin of the Parent Materials

The Parakylia layer overlies a variety of substrata in different localities. Throughout most of the zone in which the layer occurs, the substratum may be any one of the following: (1) quartzitic sandstones or quartzites, (2) the layer of quartzitic silcrete that caps the lateritic plateaux (Jessup, 1960*b*), (3) the pallid zone of the truncated lateritic profile which consists of kaolinite (derived from shales and mudstones) and weakly consolidated quartzitic sandstones, (4) an indurated fluviatile deposit.

This fluviatile deposit, for which the name Curracunya will be used in this paper, underlies the soils in many parts of the New South Wales–Queensland region. It has a maximum thickness of about 4 ft., is red in colour, very indurated, moderately to strongly vesicular, gravelly and

highly manganiferous. Microscopic examination of thin sections reveals that it consists of very thin layers and lenses of sub-rounded to rounded quartz grains separated by layers and lenses of rounded clay aggregates, that is, it retains its original sedimentary bedding.

The Curracunya deposit, the arenaceous rocks, and the pallid zone materials which directly underlie the soils are non-calcareous. On the other hand, the parent materials on which the soils developed were calcareous. The mallisols, solonetzic soils, and many grey and brown

TABLE 4

Typical Profiles of Solonetz Soils of the Parakylia Layer

Profile 1	*Profile 2*	*Profile 3*
16 miles north of Broken Hill	*115 miles north of Broken Hill*	*East of Naryilco station, Queensland*
0–5″ Apedal, sand, loam, 5 YR 6/6, slightly hard when dry, non-plastic and non-sticky when wet. Gravelly. Abrupt boundary with: 5–14″ Strong prismatic (½–1″) structure breaking very easily to strong grade angular blocky (½–¼″ peds), clay, 2·5 YR 4/8, hard when dry, sticky and very plastic when wet. Gravelly. Diffuse with: 14–35″ Apedal, clay, 5 YR 4/8, hard when dry, very plastic and sticky when wet. Gravelly. Large numbers of pockets of soft carbonate and much carbonate in fine earth. pH is alkaline throughout.	Mantle of sub-angular quartz pebbles and stones (½–3½″ in size) on surface. 0–4″ Apedal, sandy loam, 5 YR 5/6, soft when dry, non-sticky and non-plastic when wet. Trace quartz gravel. Abrupt boundary with: 4–9½″ Strong grade of prismatic (1–1½″) structure breaking very easily to strong grade angular blocky (½–¼″ peds), clay, 2·5 YR 4/6, hard when dry, sticky and plastic when wet. Trace quartz gravel. The prisms are capped by a thin (¼″) strongly vesicular, paler (5 YR 7/3) layer. Diffuse with: 9½–42″ Apedal, clay, 2·5 YR 4/8, very hard when dry, sticky and plastic when wet. Trace quartz gravel. Large amount of carbonate in fine earth and many pockets of soft carbonate. pH is alkaline throughout.	0–6″ Apedal, sandy loam, 2·5 YR 5/6, soft when dry, non-plastic and non-sticky when wet. Gravelly. Abrupt boundary with: 6–15″ Moderate grade prismatic (½–1″) structure breaking very easily to moderate grade angular blocky (½–¼″ peds), clay, 2·5 YR 4/6, hard when dry, sticky and plastic when wet. Some gravel. At the top of the prisms the clay is vesicular and paler in colour (7·5 YR 7/4). Diffuse with: 15–24″ Apedal, clay, 2·5 YR 4/6, hard when dry, plastic and sticky when wet. Some gravel. Diffuse with: 24–46″ Apedal, clay, 2·5 YR 4/6, very hard when dry, plastic and sticky when wet. Many pockets of soft carbonate; none in fine earth. pH is 7·0 in A and B_1 horizons; alkaline below.

soils of heavy texture still contain carbonate in their profiles, mostly in very large amounts. Where the soils in the Parakylia layer are red earths, carbonate that was leached from the parent materials during soil formation accumulated on the surface of the underlying Curracunya deposit or arenaceous rocks to form a layer of calcareous hardpan. The carbonate also filled cracks and fissures, and sometimes formed cylindrical masses ('pipes'), in the upper part of these substrata.

Furthermore, there are large amounts of clay in all except the sand-ridge soils, in spite of the fact that, over wide areas, the substrata are non-argillaceous. Thus the parent materials were partly, if not entirely, of transported origin.

In some localities these transported materials filled, and eventually buried, old erosion gullies that were carved in the Curracunya deposit. Although red earths, for example, subsequently formed on the new deposits, including the gully fill, the Curracunya deposit has retained its sedimentary bedding.

Gravel and stones occur in the soil profiles in many localities, indicating that at least part of the parent material was transported and deposited by water. The gravel and stones (quartz, quartzite, quartzitic silcrete, and sandstone) are sub-angular and consist of fragments of the local rocks which, as indicated above, are non-calcareous and, over wide areas, non-argillaceous. It is unlikely, therefore, that the carbonate and clay were originally laid down entirely as colluvium. Furthermore, the soils overlie non-argillaceous and non-calcareous rocks even in the highest sites in the landscape, that is, on hilltops and plateau remnants (mesas). This indicates that there were accessions of wind-transported materials.

Thus the parent material layer, on which the Parakylia soils subsequently developed, consisted partly of wind- and partly of water-transported materials.

Sand-ridges of Parakylia age occur in many localities (Fig. 2). The profile in these sand-ridges merges, at the foot of each ridge, with that in the adjacent inter-ridge area. This shows that the deposits of water- and wind-transported materials were re-sorted by wind, and that the sand-ridges were formed, prior to soil formation.

A study of the sand-ridges shows that westerly winds were responsible for transportation. The ridges are longitudinal dunes, elongated parallel to the predominating strong wind direction and lying to the leeward of the sand source (King, 1960). North of Woomera the WSW.–ENE. trending Parakylia sand-ridges overlap onto the older fine-textured stony tableland[1] soils (Jessup, 1960*c*) which lie immediately to the east. This indicates that the sand superimposed on the stony tableland soils was blown in an easterly direction. Earlier workers (Crocker, 1946; Butler, 1956) have also shown that westerly winds were responsible for transporting materials into other areas in southern Australia.

The largest amounts of wind-blown calcareous materials accumulated in the western part of the depositional zone. The mallisols and solonetzic soils in the South Australian area contain very large amounts of carbonate, and similar highly calcareous soils extend, in an unbroken belt, eastwards to the area studied (see Fig. 1) in New South Wales and Queensland. In the south-western portion of the latter area the soils are also highly calcareous. However, the amount of carbonate in the B_{ca} horizon of the soils, or in the zone below the soil profile into which carbonate was leached during soil formation, steadily declines with increasing distance to the east and north-east.

There is only one area to the west of the depositional zone where calcareous materials are exposed, namely, the Nullarbor Plain (Fig. 1), a vast area of Tertiary marine limestones. There is virtually no soil on the Plain, but soil residues, particularly carbonate nodules, are of universal occurrence. The Plain is characterized by an absence of surface drainage. It is therefore suggested that the soils originally present on it were eroded by wind and that the wind-transported materials were derived from this source. Butler (1956) has proposed the name parna for materials of this kind, namely, wind-borne materials eroded from soils.

[1] The stony tableland soils were protected from wind erosion by a well-developed surface stone pavement.

Within the zone of parna deposition there are areas of ancient (stony tableland) soils where the wind-borne materials did not accumulate. Here the present climate is arid and under these conditions the stony tableland soils support a sparse vegetative cover (Jessup, 1960*a*). When the parna was deposited, these soils would have been very sparsely vegetated, since the climate was then desertic (see Conclusions). Such conditions are unfavourable for the trapping and retention of wind-borne materials (Jessup, 1960*a*). Butler (1956) has advanced a similar hypothesis to account for 'parna-less zones' within areas of parna deposition in another part of Australia.

Except in the upper (leached) horizons which are non-calcareous, the soils contain carbonate, together with sand, gravel, or both, throughout the profile. Thus water-transported materials were deposited throughout the period of parna accumulation.

In some parts of the New South Wales–Queensland area, particularly in valleys among hills and ranges, the B_{ca} horizon of the mallisols and solonetzic soils is underlain by, and merges with, non-calcareous alluvial deposits, consisting of boulder beds, gravels, grits, sands, or gravelly clays. This indicates that parts of the landscape in this region were affected by water erosion and deposition *before* the calcareous parna was deposited.

In addition to sand-ridges, re-sorting of the wind- and water-transported deposits also resulted in the formation of gravel pavements. This may be illustrated by reference to certain solonetzic soils (those like profile 2, Table 4) in the vicinity of the Barrier Range in western New South Wales. These soils have a shallow coarse-textured A horizon which overlies fine-textured B_1 and B_{ca} horizons. Although they contain only a trace of quartz gravel and stone throughout the profile, the soil surface is completely covered by a gravel and stone pavement.

The stones, which may be up to 4 in. across, could not have been transported and deposited on the surface *after* the soil profile was developed. The velocity of flow required to transport them would have at least led to some erosion of the soils, since the latter are associated with very gently sloping country and the quartz gravel may occur several miles from its source. Furthermore, the mantle completely and uniformly covers the soil over wide areas and consists of a single layer of stones.

Although many of the surrounding soils were subsequently eroded by wind, these solonetzic soils have their A horizon intact, proving that they have not been deflated since their formation. Their surface gravel pavement has, in fact, protected them from subsequent erosion by wind.

The stone pavement must have formed after the parent material layer was laid down and before the solonetzic soil profile developed.

Surface gravel pavements that developed prior to soil formation are by no means restricted to solonetzic soils. They are commonly associated with red earths in areas which have not subsequently been affected by wind erosion.

Conclusions

This information on the nature of the soils, their parent materials, and the associated deposits, enables the sequence of events of the Para-

kylia erosional period to be reconstructed. In the country considered in the present paper, desertic conditions first prevailed in the Nullarbor Plain area, where existing soils were severely eroded by wind. The fine-textured wind-borne materials derived from this source accumulated to the east of the Plain, including the region studied in South Australia (Fig. 1). Here, therefore, the landscape must have been more completely covered with vegetation and the climate must have been less arid. But the presence of water-transported materials in the parna deposits indicates that the vegetative cover was not sufficient for complete landscape stability.

Farther to the east (in the western portion of the area studied in New South Wales and Queensland) there were no accessions of parna at this early stage. However, parts of the landscape were affected by water erosion-deposition. This is shown by the fact that the calcareous wind-borne materials deposited at a later stage overlie non-calcareous alluvial deposits. Farther east again (in the eastern portion of the New South Wales–Queensland area) the climate must still, at this early stage, have been humid enough for the maintenance of a well-developed vegetative cover and stable conditions of landscape. If this had not been so the later extension of the desertic zone (see below) would have resulted in an increase in the thickness of the deposits of water-transported materials towards the east.

As aridity increased, the desertic zone gradually became more extensive and progressively larger areas east of the Nullabor Plain were eroded by wind. The landscape became depleted of vegetation in areas where there had earlier been a sufficient cover to trap wind-borne materials. As a result, materials in the upper part of the previously formed deposits were re-sorted by wind. Sand-ridges and, where gravel was present in the deposits, gravel pavements were formed and fine-textured fractions were transported farther to the east.

Thus there was a progressive and gradual extension of (1) the zone (desertic) in which the landscape was eroded by wind, (2) the zone in which the fine-textured fractions were deposited and water erosion-deposition was occurring, (3) the zone in which there was water erosion-deposition but no accumulation of wind-borne materials, and (4) the zone in which the climate was humid and the general landscape was affected by neither erosion nor deposition. This process continued until, finally, the climate became desertic throughout the whole of the two regions studied, except for a small area in the far south-east of the New South Wales–Queensland region (east of Cobar). Here there are no sand-ridges and gravel pavements, that is, the deposits of water-transported materials and parna that were laid down were not subsequently re-sorted.

Desertic conditions, therefore, prevailed for a longer time in the west than in the east and, as a result, sand-ridges were more extensively developed in the west. They gradually become smaller and fewer in number towards the east.

The reason why the parent material layer was less calcareous towards the east can now be understood. When the calcareous wind-borne

materials derived from the Nullarbor Plain were deposited, they were mixed with non-calcareous water-transported materials. Much of the carbonate remained behind when these mixed deposits were, due to the extension of the desertic zone, subsequently re-sorted by wind. Only the carbonate in the upper part of the deposits was remobilized. This process was repeated over and over again as the desertic zone extended towards the east; the remobilized fraction was mixed, each time it was deposited, with water-transported materials.

Discussion

The Parakylia layer consists of a diversity of soils, but two major soil zones can be recognized (Fig. 2). These are a zone in which highly calcareous mallisols are dominant and one in which the dominant soils are red earths, whose development involved complete removal of carbonate from the profile. These two zones are by no means clearly defined. There is a broad transition belt, sometimes 60 miles wide, in which there are all intergrades between mallisols and red earths. The depth to which carbonate was leached progressively increases from the mallisol to the red-earth zone.

The Parakylia soils are relic, having developed under the influence of a former, wetter climate (Jessup, 1960*d*). The gradual change in soil properties across the transition belt may partly reflect the amount of leaching that occurred in the different climatic zones during the Parakylia soil-forming period. The distribution of the calcareous red earths relative to the red earths suggests that the former developed where the climate was not wet enough to permit of complete removal of carbonate from the profile, that is, where there was insufficient leaching for the development of red earths.

However, red earths and mallisols are juxtaposed in parts of the New South Wales–Queensland region. This indicates that climate was not solely responsible for determining the kind of soil that developed. North of Wilcannia, for example, there is an area of red earths within the mallisol zone (see Fig. 2). These red earths formed on parent materials that were much less calcareous than those on which the adjacent mallisols developed. Towards the eastern part of the depositional zone the calcareous parna apparently accumulated in an irregular manner and the amount of carbonate in the parent materials influenced the kind of soil that developed.

Soils that are apparently similar in many respects to the red earths and calcareous red earths discussed in this paper occur in Algeria, where their formation has also been attributed to an earlier more humid climate (Durand, 1959). In both Australia and Algeria the parent materials were calcareous. However, the calcareous component in the parent materials in the former was transported and deposited by wind, while the Algerian soils formed on calcareous rocks.

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EVOLUTION OF THE TWO YOUNGEST (QUATERNARY) SOIL LAYERS IN THE SOUTH-EASTERN PORTION OF THE AUSTRALIAN ARID ZONE

II. THE BOOKALOO LAYER

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Summary

The calcareous materials in the deposits, on which the Bookaloo soils developed, were transported by wind. They were derived through deflation of older soils that occurred both within the region and in an area lying to the west. Wind erosion in the region was confined to a zone in which the climate became arid. Beyond the arid zone there was a sufficient cover of vegetation for landscape stability. In some localities deposits of wind-blown materials accumulated in the beds of relic streams. The present drainage lines are incised in these deposits.

The soils, whose profiles are characterized by only weak horizon differentiation, developed following the onset of wetter climatic conditions.

Introduction

TRUNCATED lateritic soils occur on remnants of an old land surface in arid Australia (Jessup, 1960*b*). After the formation of the younger land surface, above which the lateritic plateaux rise, the stony tableland soil layer developed (Jessup, 1960*c*).

Erosion subsequently destroyed this layer in many areas. Then two younger soil layers, the older of which has been called the Parakylia layer and the younger the Bookaloo layer, developed (Jessup, 1960*d*). The evolutionary history of the Parakylia soil layer was presented in a previous paper (Jessup, 1961).

The present paper discusses the Bookaloo soil layer and the origin of the materials on which the soils developed. Investigations were carried out in two extensive and representative areas in the south-eastern portion of arid Australia (see Jessup, 1961).

Characteristics of the Soils

The Bookaloo layer consists, practically everywhere, of soils with characteristics like the grey-brown and red calcareous desert soils[1] as defined by Stephens (1956). These soils vary in depth up to a maximum of 3 ft. Carbonate is usually present in large amounts throughout the profile (profiles 1, 2, and 3, Table 1)[2] but may occasionally be absent from the upper inch or so (profile 4, Table 1). The carbonate is principally dispersed through the fine earth; it never occurs in nodular form.

[1] Laboratory analyses of grey-brown and red calcareous desert soils have been presented by Blackburn and Baker (1953) and Jackson (1958).

[2] All Munsell colour notations in the Tables refer to dry soil. Consistence terms follow the system described in the U.S.D.A. Soil Survey Manual, Handbook No. 18, 1951. The term apedal is used for soil that is structureless.

The absence of marked carbonate segregation together with weak textural differentiation (see Table 1) indicates that these soils, which are paleosols (see Jessup, 1960*d*), were subjected to little or no leaching during their formation.

Sand-ridges also form part of the Bookaloo layer in a few localities, but the sand-ridge areas are too small to appear on Fig. 1. Sometimes the sand-ridges occur as isolated dunes that are directly superimposed upon the Parakylia soil layer (profile 1, Table 2). In other localities, the

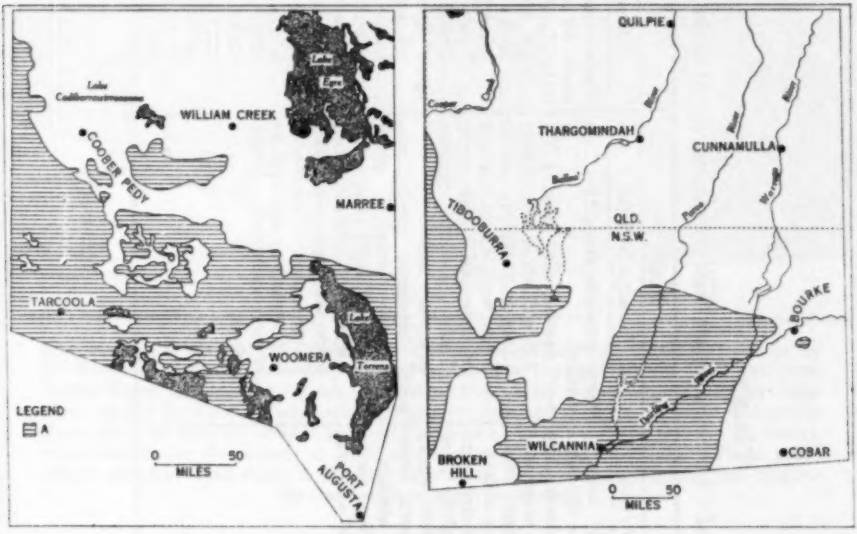

FIG. 1. Showing the distribution (zone A) of the grey-brown and red calcareous desert soils in the areas studied in South Australia (*left*) and New South Wales–Queensland (*right*).

sand-ridge profiles merge, at the foot of the dunes, with grey-brown and red calcareous desert soils (profile 2, Table 2).

The Origin of the Parent Materials

The Bookaloo layer directly overlies a diversity of substrata. Over wide areas it is underlain by the Parakylia soil layer, but this layer is absent in some places. Here the Bookaloo layer directly overlies either non-calcareous rocks such as sandstones and quartzites, the exposed pallid zone of the lateritic soil profile, or a layer of wind-blown gypsite (see below).

Many of these substrata are non-calcareous, whereas the Bookaloo soils are highly calcareous. Furthermore, the soils overlie non-calcareous substrata even on the highest parts of the landscape (hilltops and plateaux). The calcareous parent materials must, therefore, have been transported and deposited by wind.

TABLE 1

Representative Profiles of Grey-brown and Red Calcareous Desert Soils (Stephens, 1956) of the Bookaloo layer

Profile 1	*Profile 2*	*Profile 3*	*Profile 4*
Mundowdna	*31 miles north of Hesso*	*Barnato, N.S.W.*	*Barnato, N.S.W.*
On surface some silcrete gravel (¼–1″). 0–¼″ Surface crust, clay loam, 7·5 YR 6/6, soft when dry, slightly sticky and slightly plastic when wet. Carbonate in fine earth. Diffuse boundary with: ¼–15″ Weak grade of subangular blocky (¼–½″ peds) structure, light clay, 7·5 YR 6/6, slightly hard when dry, sticky and slightly plastic when wet. Large amount of carbonate in fine earth; soft carbonate also occurs in pockets. Trace gravel.	0–12″ Apedal, sandy loam, 5 YR 5/6, soft when dry, non-sticky and non-plastic when wet. Very large amount of carbonate in fine earth. Diffuse boundary with: 12–24″ Apedal, sandy clay loam, 5 YR 5/6, slightly hard when dry, slightly sticky and slightly plastic when wet. Very large amount of carbonate in fine earth; many pockets of soft carbonate.	Some quartzite gravel (¼–2″) on surface. 0–3″ Apedal, silty loam, 5 YR 5/6, soft when dry, slightly sticky and slightly plastic when wet. Large amount of carbonate in fine earth. Trace gravel. Diffuse boundary with: 3–13″ Moderate grade subangular blocky (¼″ peds) structure, light clay, 5 YR 5/6, slightly hard when dry, sticky and plastic when wet. Large amount of carbonate in fine earth; many pockets of soft carbonate. Trace gravel.	Trace quartzite gravel and stones on surface. 0–3½″ Apedal, silty loam, 5 YR 4/6, soft when dry, slightly sticky and non-plastic when wet. Non-calcareous. Trace quartzite gravel. Diffuse boundary with: 3½–11″ Apedal, silty loam, 5 YR 5/6, soft when dry, slightly sticky and slightly plastic when wet. Large amount of carbonate in fine earth. Trace gravel. Diffuse with: 11–35″ Apedal, silty loam, 5 YR 6/6, slightly hard when dry, slightly plastic and slightly sticky when wet. Large amount of carbonate in fine earth; many small pockets of soft carbonate. Trace gravel.

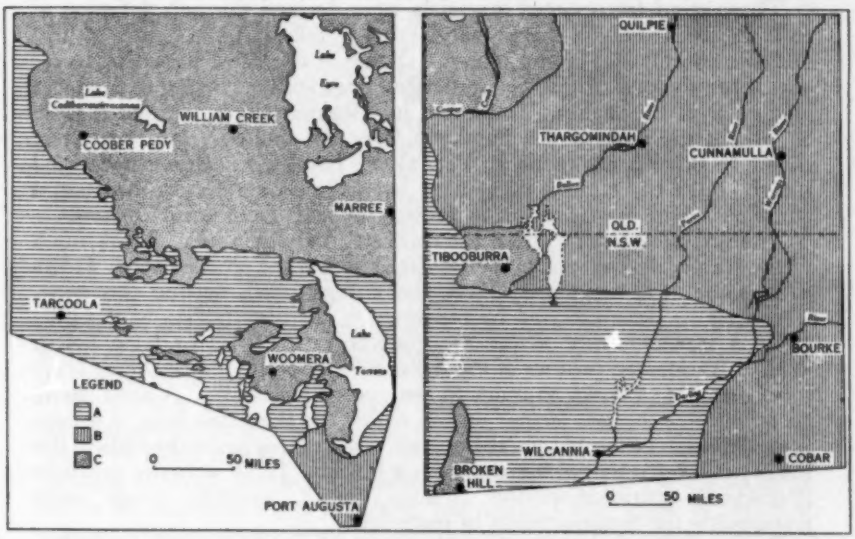

FIG. 2. Distribution of the unstable (arid) and stable (relatively humid) zones during the Bookaloo erosional period in the areas studied in South Australia (*left*) and New South Wales–Queensland (*right*). A, zone within which the existing (Parakylia) soils were eroded by wind because arid climatic conditions prevailed. B, zone where the Parakylia soils were not eroded because the climate was more humid and the vegetative cover was better developed. C, zone where stony tableland soils occur. These soils, which are older than those in the Parakylia layer, were protected from wind erosion by their surface stone pavement.

TABLE 2

Typical Profiles of Bookaloo Sand-ridge Soils

Profile 1	*Profile 2*
111 miles north of Broken Hill	*Curdimurka*
0–90″ Sand, 2·5 YR 4/8. Diffuse boundary with: 90–105″ Apedal, clayey sand, 2·5 YR 4/8, hard when dry, non-sticky and non-plastic when wet. This profile is at crest of dune. Sand-ridge is superimposed upon solonetz of Parakylia age.	0–27″ Sand, 10 YR 7/6. Diffuse boundary with: 27–36″ Apedal, clayey sand, 7·5 YR 6/6, hard when dry, non-sticky and non-plastic when wet. Diffuse with: 36–54″ Apedal, clayey sand, 5 YR 6/8, consistence as above. Large amount of carbonate in fine earth; many pockets of soft carbonate. This profile is in lower slope of dune. Sand-ridge merges (at foot of ridge) with grey-brown and red calcareous desert soil.

These wind-transported materials were derived through deflation of soils in the Parakylia layer; wind erosion followed the onset of arid climatic conditions (Jessup, 1960*d*). Some of the wind-blown material[1] was of purely local origin, being deflated from soils occurring in the more arid parts of the region. Truncated profiles occur only in zone A (Fig. 2), where the soils in the Parakylia layer are mallisols and solonetzic soils. In other areas (zone B, Fig. 2) the Parakylia soils are preserved intact. Here the climate must have been humid enough to maintain a sufficient cover of vegetation to protect the soils from wind erosion.

The Bookaloo layer overlies the truncated Parakylia soils. Thus much of the locally derived parna accumulated within the eroding zone. However, some of it was transported, and accumulated, beyond this zone. This may be demonstrated by reference to the distribution of the soils along a traverse from Wilcannia eastwards to Cobar in New South Wales. Truncated profiles of Parakylia soils underlie the Bookaloo layer for a distance of some 50 miles to the east of Wilcannia. A zone, some 60 miles wide, occurs farther east in which the Bookaloo layer is superimposed upon uneroded Parakylia soils. East of this again the soils in the Parakylia layer were neither eroded nor buried. Thus, as in the previous (Parakylia) erosional period (Jessup, 1961), westerly winds were responsible for transportation of materials.

However, there must also have been accessions of calcareous materials from an extraneous source. The deposits on which the Bookaloo soils developed could not have consisted entirely of materials derived from the Parakylia mallisols and solonetzic soils. The upper horizons of the latter are non-calcareous, while the Bookaloo soil layer is highly calcareous throughout its entire depth. It is suggested that, as in the Parakylia erosional period (Jessup, 1961), there were again accessions of parna derived through deflation of calcareous soils on the Nullarbor Plain which lies to the west of the region studied.

A vast area around Lake Eyre is occupied by ancient stony tableland soils (Jessup, 1960*c*) which, in turn, overlie the pallid zone of the older lateritic soil profile. Traversing this area are many broad (dry) creeks that rise among remnants of the lateritic plateau and discharge into Lake Eyre. The creeks, which drain country that is non-calcareous, are incised in the pallid zone of the lateritic profile. In spite of this there is a layer of highly calcareous Bookaloo soil (grey-brown and red calcareous desert soil) in the beds of these creeks. The calcareous parent materials must have been deposited by wind.

A layer of fine-grained (powdery) gypsum, often 2 ft. thick, underlies the Bookaloo soil in these creeks. It is evident from their nature that the materials in this gypsite layer were also deposited by wind. The source of the gypsum and the significance of its presence will be discussed later in this paper.

Thus first gypseous and later calcareous deposits accumulated in existing (inherited) drainage lines in the Lake Eyre region during the arid Bookaloo erosional period. Narrow channels which form the present

[1] Butler (1956) proposed the term parna for materials of this kind, namely, wind-borne materials eroded from soils.

drainage lines have since been cut in these deposits. The present drainage lines, therefore, are incised in wind-blown deposits that accumulated in, and partly filled, the broad beds of earlier streams.

The gypseous and calcareous materials did not accumulate on the ancient (stony tableland) soils that occur between the creeks. The reason for this can be deduced from a study of the present vegetative cover. Under the present arid climate, the fine-textured stony tableland soils support only a sparse vegetative cover. On the other hand, the drainage lines provide a comparatively favourable habitat for plants and, by comparison, are well-vegetated. As the climate of the Bookaloo erosional period was similar to the present climate (see Conclusions) there would have been a comparable vegetative pattern. Since a cover of vegetation is necessary to trap wind-blown materials (Jessup, 1960*a*), it is not surprising that they accumulated in the beds of the creeks but not on the stony tableland soils.

Within the Lake Eyre region these wind-borne materials did not accumulate solely in the beds of the old creeks. They also filled the 'cups' of fossil mound-springs. The mounds formed by these ancient springs, which have been discussed by Ward (1921), rise 60 to 80 ft. above the adjacent stony tableland soil plains. The 'cups' or 'craters', which contained water when the springs were active, are now filled with the gypseous and calcareous deposits, the composition and nature of which are in marked contrast to the materials in the mound-springs themselves.

Similar deposits were also laid down on other parts of the landscape in this region. North of Woomera (at Billa Kalina) for example, a layer of gypsite up to 2 ft. thick, followed by one of calcareous material of similar thickness, was laid down on a low plateau over a bed of limestone.

The presence of these deposits on even the highest features in the landscape (mound-springs and plateaux) is further proof that the materials in them were wind-transported.

The soils that formed on calcareous materials, transported beyond the areas in which the Parakylia soils were eroded, have a finer texture (profiles 1, 3, and 4, Table 1) than those formed on materials that were deposited adjacent to their source (profile 2, Table 1).

The Bookaloo layer is not superimposed upon solonetzic soils of Parakylia age in the areas studied. Like the stony tableland soils, the solonetzic areas did not trap and retain wind-borne materials.

The Bookaloo soils did not develop entirely on wind-transported materials in all localities. Many of the soils (see profiles 1 and 3, Table 1) contain small amounts of gravel throughout the profile. In these areas materials of water-transported origin were laid down at the same time as the wind-borne ones.

Conclusions

Following the onset of aridity there were large areas (zone A of Fig. 2) that were sparsely vegetated for long periods, with the result that existing (older) soils were eroded by wind. However, there was sufficient vegetation, within the eroding zone, to trap some of the wind-blown material.

Conditions during the Bookaloo erosional period, therefore, were similar to existing conditions in the more arid parts of the areas studied. In these areas the soils are eroded by wind during droughty periods, even where the vegetative cover has not been depleted as a result of man's activities. However, there is a sufficient cover of vegetation to trap at least part of the wind-blown material within the eroding zone (Jessup, 1960*a*).

The climate of the Bookaloo erosional period could not have been as arid as that of the previous (Parakylia) erosional period. During the Bookaloo erosional period there was a sufficient cover of vegetation within the eroding zone to trap wind-borne materials. In contrast, the climate became so desertic and the vegetation so sparse during the Parakylia erosional period that wind-borne materials were not trapped within the eroding zone (Jessup, 1961). Furthermore, wind erosion affected a smaller area in the Bookaloo, than in the Parakylia, erosional period. During the Bookaloo, the landscape was stable in the eastern and north-eastern parts of the area studied in New South Wales and Queensland (zone B of Fig. 2). On the other hand, the zone in which the landscape was eroded by wind during the Parakylia overlapped practically the whole of this area (Jessup, 1961).

It has been shown that first, a layer of wind-blown gypsite and later, one of calcareous parna accumulated in the beds of creeks, 'cups' of extinct mound-springs and other sites in the Lake Eyre region during the Bookaloo erosional period. Westerly winds were responsible for transporting the parna. The gypsum was also blown from the west, being deflated from gypseous deposits that had accumulated in the playa lakes. Remnants of the gypseous beds still survive in some of the playas (Jessup, 1960*a*). There was no other part of the landscape where gypsum was exposed. From the depositional sequence (gypseous followed by calcareous deposits) it appears that the lakes dried out, and materials were blown from their beds, before the Parakylia mallisols and solonetzic soils were eroded, that is, before aridity became severe enough to initiate general landscape instability.

Discussion

Development of the grey-brown and red calcareous desert soils, the dominant soils in the Bookaloo layer, involved only slight segregation of carbonate and clay. Carbonate usually occurs throughout the entire profile in the fine earth and there is only weak textural differentiation. This is in marked contrast to most of the soils that developed during the soil forming period of the previous (Parakylia) cycle when, even in the driest areas, there was considerable segregation of clay and carbonate (Jessup, 1961). The climate of the Bookaloo soil forming period, therefore, was either drier than that of the Parakylia period or humid conditions prevailed for a much shorter time. The Parakylia soils that are buried beneath the Bookaloo soil layer (Jessup, 1960*d*) have characteristics like those that are exposed at the surface of the landscape. The Bookaloo soil-forming period, then, did not significantly affect these older soils.

The importance of wind transportation and deposition in the origin of the parent materials of some Australian soils has been discussed by several earlier workers. Crocker (1946) showed that certain soils in the southern portion of South Australia formed on deposits of wind transported calcareous materials blown from old coastal dunes and dune sheets. Butler (1956, 1958), Butler and Hutton (1956), and van Dijk (1958) demonstrated that there are a number of superimposed soil layers in the Riverine Plain of New South Wales and that several of these layers formed on deposits of wind-blown materials. Butler (1956) suggested that the wind-deposited materials were derived through deflation of soils lying to the west of the depositional zone.

Most of the soils in the south-eastern portion of the Australian arid zone formed on parent materials that were, partly or entirely, transported and deposited by wind. Thus, Jessup (1960*c*) demonstrated that the stony tableland soils, paleosols of Quaternary age that occur over wide areas, formed on wind-blown materials derived from old lacustrine sediments. Highly calcareous materials, derived through erosion of older soils lying farther to the west, were transported into this part of the Australian arid zone by wind during the Parakylia erosional period and contributed to the deposits on which the Parakylia soils developed (Jessup, 1961). In the present paper it has been shown that the soils in the Bookaloo layer also formed on deposits of wind-blown materials.

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SOIL STUDIES AT SWAN HILL, VICTORIA, AUSTRALIA

I. SOIL LAYERING

H. M. CHURCHWARD

Summary

Much of the variation in soil profiles at Swan Hill is due to the superposition of soils (one upon the other).

This paper deals with the principles by which interlayer variations may be distinguished from intralayer variations. The latter have an interdependence corresponding to the eluvial-illuvial relationship, whilst the former show a discordant and even random relationship. The discordant relationship between layers is due to the variable truncation (by erosion) of each soil layer prior to its burial by further depositional material. In the riverine layers there has been no erosion, and soils overlie one another conformably. Their distinctness is proved by the recurrence of eluvial-illuvial patterns of distribution down the vertical axis. The regular waxing and waning of morphological features—cutans, pedality, visible porosity, and coherence—are used as diagnostic features.

I. *Introduction*

PROFILE studies at Swan Hill, Victoria, have revealed a diversity of materials both from site to site and in passing down a vertical section. This diversity involves fabric (Kubiena, 1938), texture, consistency, presence of lime, and variations of colour.

It is proposed to discuss the inter-relationship of these diverse materials and to show that though some of the diversification is pedogenetic in nature, much of it is related to distinct depositional layers or strata. These latter represent the different erosion-deposition events in the history of the landscape and ancient phases of soil development. This paper will be confined to the identification and proof of the separate layers, an outline of the bases for distinguishing intralayer (pedogenic) variation from interlayer variation, and an examination of some of the implications of the occurrence of both kinds of variation in profile assemblages in the Swan Hill region.

Swan Hill is situated on the Murray River in the eastern portion of the Mallee Region of north-western Victoria, (see Fig. 1). The locality has a warm temperate to semi-arid climate, the rainfall being 13 in., distributed throughout the year, with a winter maximum.

The area occupies a plain of deposition, the principal features of which are the result of aeolian and riverine action. The landscape has been dealt with in more detail elsewhere (Churchward, 1960*a* and *b*). The general relationship is that the western and north-western part of the district is dominated by aeolian materials, whilst the eastern and south-eastern sections largely comprise extensive alluvial deposits in a typical riverine landscape. The principal topographic features of the aeolian landscape are parallel dunes, having an approximate east-west orientation, lunettes (Hills, 1939) and clayplains. On the other hand, the riverine landscape is featured by prior stream levees and flood plains.

II. *Layer Nomenclature and Description*

The study of the soils at Swan Hill resulted in the recognition of five separate layers of material in the aeolian landscape and four in the riverine landscape. The layers in the aeolian landscape, from the surface downward, are named the Piangil, Kyalite, Speewa, Bymue, and Tooleybuc. The layers in the riverine landscape in the same order, are

FIG. 1. Location plan of the Swan Hill area.

the Coonambidgal, Mayrung, Quiamong, and Katandra, following the nomenclature of Butler (1958).

The Piangil layer is an incoherent sandy material, having Munsell colour notations ranging from 7·5 YR 7/6 to 10 YR 7/6 and showing a marked degree of thin bedding. There are no orderly changes in properties with depth.

The Kyalite layer comprises a porous, weakly coherent material having no tendency to form large structural units and showing little, if any, change in clay content with depth. Pale, dull colours dominate:

the general Munsell colour notation is from 7·5 YR 6/6 to 5 YR 5/8. Lime, if present, occurs only in the fine earth and not as segregations. Nevertheless, lime may be leached from the surface 2 to 3 in. No thin bedding is visible in the upper 24 in.

The Speewa layer shows some tendency to form peds as well as having definite segregation of clay and lime down the profile. There is some limited appearance of weakly developed clay faces on the ped surfaces in portions of the profiles. Lime occurs as segregations as well as in the fine earth. Colours are redder in hue than in the Kyalite layer, generally ranging from 5 YR 5/8 to 2·5 YR 4/8. The material is moderately porous, and more strongly coherent than the Kyalite layer.

The Bymue layer has an increased tendency to form peds, while zones of lime and clay maxima are at a greater depth than in the Speewa layer. Material of this layer shows a more general occurrence of glossy clay faces, is visibly less porous and the lime is more strongly segregated than in the Speewa layer. Furthermore, it is firmer and more coherent than the latter material, while the general Munsell colour notation ranges from 5 YR 4/8 to 2·5 YR 4/8.

The Tooleybuc layer usually comprises mottled labile and plastic clays, the greater proportion of this material having a highly glossy, or waxlike appearance. More sandy materials may also occur with clay faces as a prominent feature. Materials of this layer have very few visible pores and a marked tendency to coarse structural aggregation.

The uppermost riverine depositional system is the *Coonambidgal* (see Butler, 1958, for this and other riverine layers). It varies from grey (2·5 Y 6/2) silty loams to silty light clays which are friable, porous, highly micaceous and have considerable root, worm, and insect voids. There is no textural differentiation.

The riverine system below the Coonambidgal is the *Mayrung* layer which shows differentiation of lime and frequently of clay, while there is quite a definite structural development. The materials are moderately firm and plastic, as well as showing clay skins on the peds. The layer frequently overlies the *Quiamong* system which in this situation occurs as unweathered riverine deposits, most strikingly as a grey (2·5 Y 5/2), non-calcareous, micaceous silty clay loam to medium clay. However, when exposed at the surface this layer shows differentiation of clay and lime and the development of definite peds.

Immediately below these deposits is the *Katandra* layer. This occurs most frequently as a dense, mottled, light grey and yellowish brown, heavy clay with many clay faces and a definite blocky structure. This material is very firm and usually very plastic.

III. *The Proof of the Separateness of the Aeolian Layers*

The occurrence of a vertical arrangement of layers of soil material may well indicate the horizons of one soil profile. In such a system the layers, or soil horizons, are interdependent on the basis of eluvial and illuvial relationships and changes in one layer are reflected by complementary changes in the other layers. If an arrangement of layers has no such relationship between upper and lower members it may be

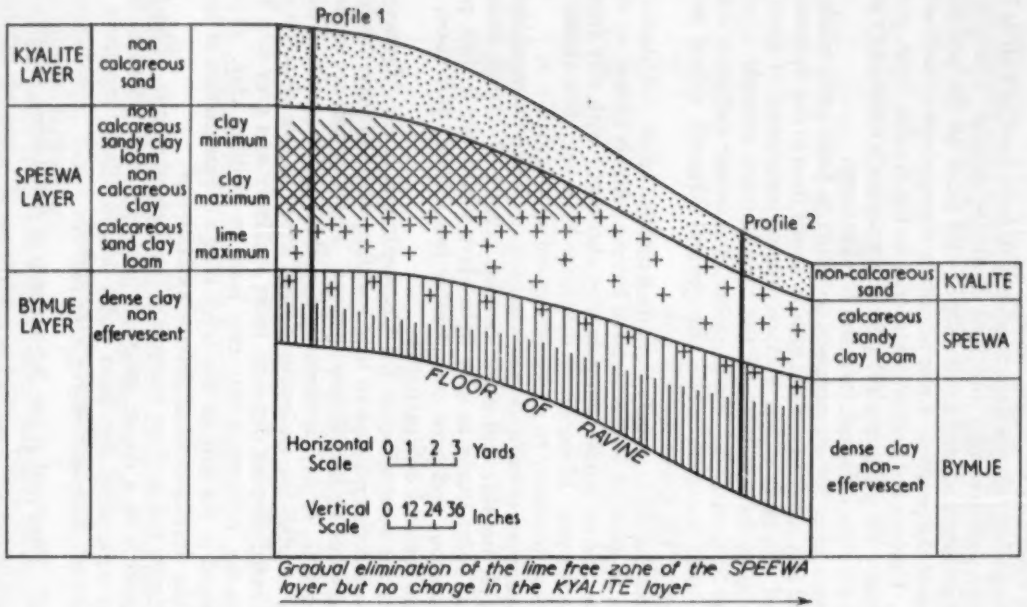

FIG. 2. Section showing the independent relationship of the Kyalite to the Speewa layer.

concluded that their juxtaposition is the result of some process other than soil development. Differential depositional processes may be a likely alternative explanation of the situation, and such depositional layers would have a degree of independence from one another, for which evidence should be sought. Hence the juxtaposition of the soil material on each of the several substrates is a random relationship, and is to be contrasted with the complementary relationship between pedogenetic horizons. The significance of the distinction between the propinquity of materials having genetic relatedness, and of materials not having genetic relatedness, is emphasized here. Walker (1958) has referred to the latter as the *principle of random association* and has used it in distinguishing between soil layers. It should be noted that random association refers to the superposition of soil material on soil material and not to the relationship of one ground surface to another which, as will be seen subsequently, is orderly.

The Piangil layer is found to overlie materials of either the Kyalite or the Speewa layer and, furthermore, there is no consistent relationship between variations in texture of these substrata and those of the Piangil layer. In addition, material of this layer is more frequently associated with the works of man, such as fences, fields, and buildings, than with the principal landscape features: there is little doubt concerning the independence of this layer.

Evidence supporting the proposed independence of the Kyalite, Speewa, and Bymue layers is provided most frequently by the chance superposition of either calcareous and non-calcareous materials of one of these layers on either the non-calcareous or calcareous zones of the underlying layer. A similar randomness in interlayer relationships was seen in features such as texture, fabric, consistency, and colour.

Proof that the Kyalite layer is a separate entity is provided by a section in an erosion gully on the steeper slope of a lunette. The site is in the centre of portion 8, Parish of Merran, County of Wakool, N.S.W. The arrangement of materials is shown in Fig. 2. Profile 1 of this cutting shows a non-calcareous Kyalite sand overlying a non-calcareous clay which becomes a calcareous sandy clay loam with depth. The material shown as Kyalite conforms to the specifications given above: it is a weakly coherent sand, while the substrate shows the features of the Speewa layer. Farther along this gully, profile 2 shows the Kyalite layer continuing unchanged over a calcareous Speewa material. Thus, although there is no change in the Kyalite layer, the change in the Speewa at the interface is a radical one; the Kyalite layer shows a significant degree of randomness in its association with the underlying materials. It is considered, therefore, to be an independent body. Further evidence supporting the proposed independence of the Kyalite layer is provided by the chance superposition of either calcareous or non-calcareous Kyalite material on either the non-calcareous or calcareous zones of the Speewa layer. Such relationships are of frequent occurrence in this locality.

A similar line of reasoning can be employed to prove the independence of the Speewa layer: it can be found overlying a variety of substrates,

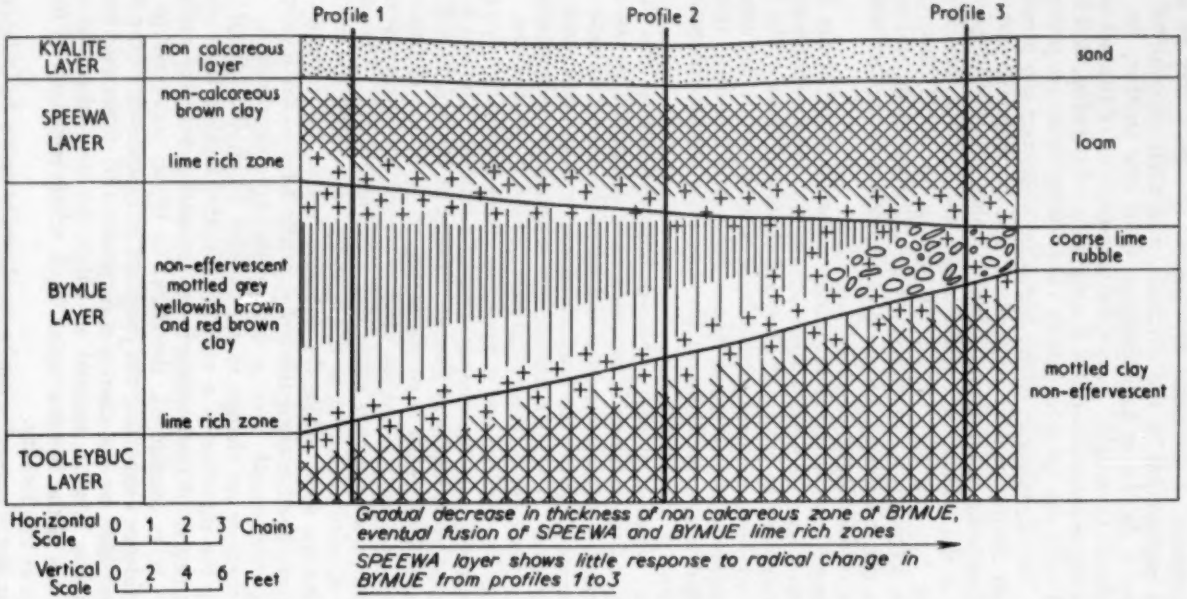
Profile 1
Profile 2
Profile 3
KYALITE LAYER
non calcareous layer
sand
SPEEWA LAYER
non-calcareous brown clay
lime rich zone
loam
BYMUE LAYER
non-effervescent mottled grey yellowish brown and red brown clay
lime rich zone
coarse lime rubble
mottled clay non-effervescent
TOOLEYBUC LAYER
Horizontal Scale 0 1 2 3 Chains
Vertical Scale 0 2 4 6 Feet
Gradual decrease in thickness of non calcareous zone of BYMUE, eventual fusion of SPEEWA and BYMUE lime rich zones
SPEEWA layer shows little response to radical change in BYMUE from profiles 1 to 3

FIG. 3. Section along the drain at Woorinen, Victoria, showing the independent relationship of the Speewa and Bymue layers.

commonly the Bymue layer, but this may disappear and the Tooleybuc becomes the substrate. This situation was studied in an open drain at Woorinen, not far from Swan Hill in Victoria (see Fig. 3). This is drain no. 1EM of the Woorinen Irrigation Settlement and is located in Allotment 14 of A, Parish of Tyntynder, County of Tatchera, Victoria. In passing, it will be noted that a uniform sheet of Kyalite sand covers the whole transect. Profile 1 shows 18 in. of material conforming to the specifications of the Speewa material overlying 2 ft. of Bymue layer. The latter is non-calcareous in the upper part though calcareous below, but pockets and ped coatings of lime occur on the upper fringe of the Bymue. If this system, composed of elements of the Speewa and Bymue layers, is the normal genetic horizon development of a soil profile, it would be expected that a consistent relationship between layers would be maintained. However, in following the drain it is found that the Bymue layer gradually tapers out through profile 2 until it is almost completely eliminated. Furthermore, there is a progressive increase in proportion of coarse, hard, lime concretions in this layer while at the same time there is no appreciable change in the Speewa layer. Thus, if the relationship between the Speewa and the Bymue layer, as in profile 1, is the result of pedogenesis, then changes in the Bymue layer should be reflected in changes in the overlying Speewa layer which is not the case.

A similar approach is used to establish the independence of the Bymue layer from the Tooleybuc. The general uniformity of the Tooleybuc layer contrasts with the wide range of features of the Bymue layer; heavy clays of the Tooleybuc layer may be the common substrate to the sandy clay loams, light clays, and heavy clays of the Bymue layer.

It will be noted that although these layers are independent of each other and that their relationships are not of the eluvial-illuvial type, there is nevertheless a specific order of layers. This order, passing from above to below, is Piangil, Kyalite, Speewa, Bymue, and Tooleybuc; members may, however, be missing from this sequence at specific sites.

IV. *Soil Profiles on the Layers*

Within the layers an orderly pattern of variation is frequently manifest in vertical sections. The most striking of these is the increase in lime, and of clay to some regular depth below the surface of the layer. Such consistent trends are to be contrasted with the random relationship between layers. Furthermore, the zonation of features within the layers shows interdependent relationships of the eluvial-illuvial type, and changes in one horizon are reflected by complementary changes in other horizons. Profile arrangements of this type are generally endorsed as essential features of soil development or pedogenesis. Jenny (1941) writes of the directional nature of the distribution of soil features, each distribution pattern having a predominantly vertical orientation, so that they may be spoken of as 'depth functions'. These have also been referred to and studied by Dickson and Crocker (1954) and Crocker and Major (1955). Depth functions are generally simple in form, with trends towards and away from a maximum, or increasing or decreasing trends

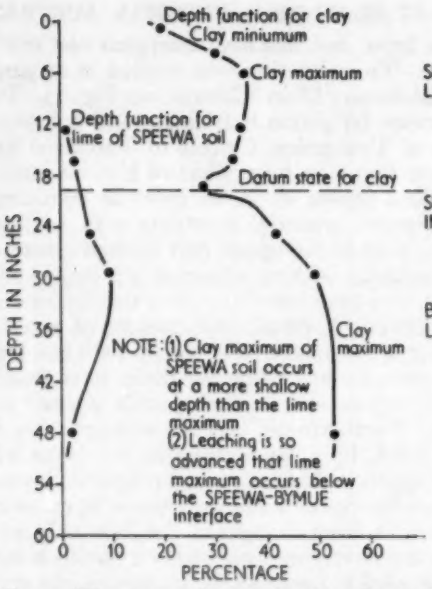

FIG. 4. The nature of depth functions for the Speewa layer. (The boundary between layers as shown on the right was determined by fabric characteristics.)

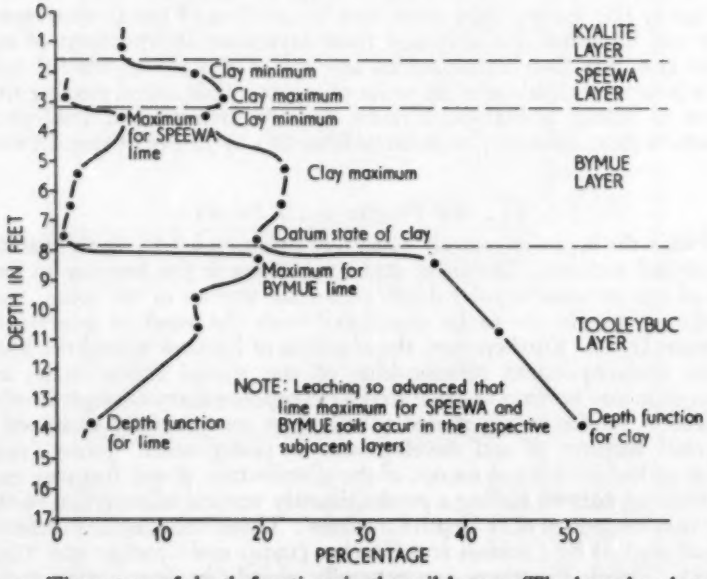

FIG. 5. The nature of depth functions in the soil layers. (The boundary between layers as shown on the right, was determined by fabric characteristics.)

alone. A soil system may be defined by the totality of its depth functions for different properties.

The properties providing the significant depth functions in the soils referred to by Jenny and by Crocker and others include organic matter, chloride, and salts of comparable solubility, and iron and aluminium contents. However, soil properties providing the more striking depth functions at Swan Hill are clay and lime content, fabric, and consistency.

The examination of depth functions of a Speewa profile reveals the distribution curves for clay and lime (see Fig. 4). This vertical distribution shows a minimum at the soil surface increasing to a maximum some depth below and then frequently decreasing again to another lower value. Thus, there is a clay minimum as an A horizon at the surface, passing downwards to a clay maximum, or B horizon, and thence to a datum state or C horizon. Comparable differentiation in lime content occurs.

Depth functions in the Bymue layer (Fig. 5) indicate that it also has trends in properties down the vertical axis comparable with the Speewa. The maximum and minimum in the depth functions for lime and clay of the Bymue profiles have a similar form to those of the Speewa soils. However, these are expanded along the vertical axis, so that for instance, while the clay maximum in the Speewa profile occurs at 12 in., that of the Bymue is at 36 in.

Inaccessibility owing to depth has resulted in a paucity of information regarding depth functions of the Tooleybuc layer. However, in the medium- and coarse-textured materials of this layer the clay maximum has been seen to occur at about 6 to 7 ft. On the other hand, the fine-textured materials of the layer show little variation in texture with depth. The material is dense and plastic with the clay in a waxlike form throughout the peds and it seems comparable with the gumbotil (Kay, 1930) of North America which is regarded as being indicative of a high degree of weathering and soil formation.

In general, in passing down profiles of any one layer the values for clay and lime increase from the surface down to a maximum and from there decrease towards the base of the profile. Similar waxing and waning trends are expressed in the structure, soil fabric, and consistence properties. The pedality, frequency, and glossiness of clay coatings and bridges (Brewer, 1960), and the firmness of peds, were all at a maximum toward the centre of each soil profile. These properties either develop abruptly or more gradually in the upper part of the profile as the modal point of the B horizon is approached, and below they generally very gradually decline. The latter trend continues, if the thickness of the layer permits, until a characteristic C horizon state is reached, with low or no pedality, no clay faces, and a soft, porous consistence. These trends of waxing and waning of properties enable buried soils and even the lower parts of the soils to be identified as such. During these studies it became evident that the range of each of these trends is dissimilar and the differences so characteristic that they can be used to distinguish one soil layer from the other.

It has previously been mentioned how separateness of the soil layers

can be established on the principle of random association: it is now shown that the separateness of the soil layers may be proved alternatively on the basis of depth functions which may be based on one vertical section only.

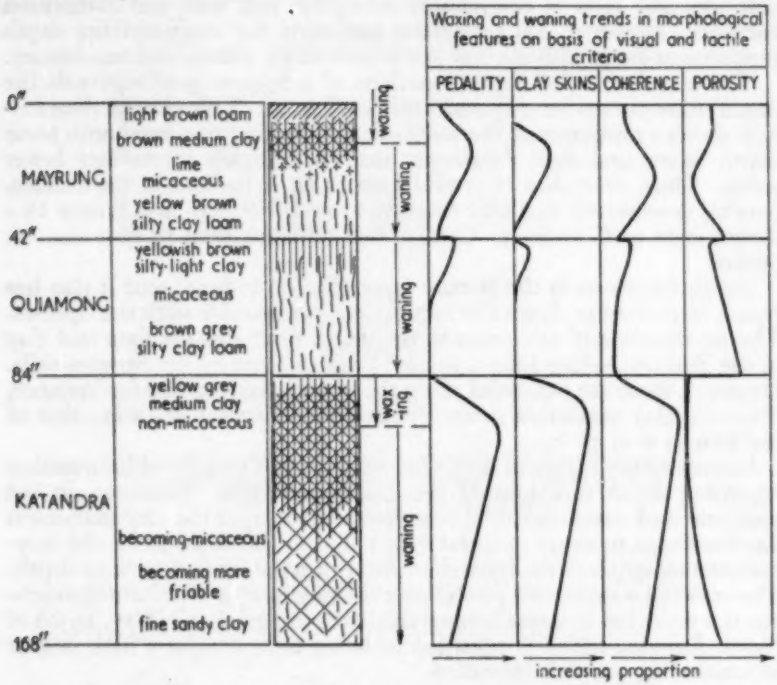

FIG. 6. Compound profile showing repetition of patterns of variation due to superposition of soils.

V. *The Proof of the Separateness of the Riverine Layers*

The separateness of the riverine layers in this locality cannot be proved on the basis of association as with the aeolian layers. The association in the latter is essentially determined by the fact of variable soil erosion (see below) between one soil layer and another. However, in the riverine landscape erosion has been limited to the close environs of the respective prior stream courses. Thus in this landscape one soil overlies the other conformably (Butler, 1959). The unity of their depth functions and the repetition of weathered and unweathered states in a vertical transect are the criteria proving the separateness of the several riverine layers.

An example of the kind of proof offered occurs in a profile illustrated in Fig. 6. This shows the repetition in a vertical plane of features resulting from processes of soil formation. In this section the Mayrung layer occurs at the surface as a differentiated soil having 4 in. of brittle

loam over a brown plastic medium clay. This clay horizon shows a high development of peds with clay skins and firm consistency, and for this profile represents a maximum development of these features. From 24 in. this material gradually passes down into a yellowish-brown, porous, friable, apedal, silty clay loam and at the same point, trace amounts of lime rubble occur. A minor, but definite, change occurs at about 42 in. to a mottled yellowish-brown and brownish-grey silty light clay which is very slightly less porous and firmer than the overlying material. This condition, nevertheless, progressively changes to a very porous, friable state by 50 in. At 84 in. there is a sharp increase in density, the material below this depth being a yellowish-grey, dense, coarse blocky or platy, silty, non-micaceous, medium clay. This is the Katandra layer. Its peds are very firm with smooth, waxy fracture and cleavage faces. By about 10 ft. it becomes more friable, more micaceous, and shows less glossy clay faces. With depth it assumes a condition of consistence that is comparable with the C horizon of the Mayrung soil.

Further support to the proposition of the separateness of the riverine layers comes from the nature of their distribution. The Coonambidgal occurs as an overlay in only about 10 per cent. of the area and its thickness varies from a few inches to about 36 in. without the nature of the underlying layer, the Mayrung or the Quiamong, showing any sympathetic variations. There appears to be no important difference between the profile trends in the Mayrung layer whether Coonambidgal overlies it or whether it is the surface exposure. Independence of the Mayrung and Quiamong layers is supported by the occasional occurrence of the Mayrung resting directly on Katandra. The Katandra occurs universally beneath the riverine landscape, always as a buried soil.

VI. *The Superposition of Part-soils*

The data in Figs. 2 and 3 indicate that the buried soil may often have been partly truncated before burial. In Fig. 2, in compound profile 1, the Speewa soil may be recognized as a more or less complete profile, because it has a clay and fabric maximum placed vertically between upper and lower minima (the A and C horizons respectively) and because a lime maximum also occurs below, but in general conformable relationship to it. The material at the base of the Speewa profile is predominantly a friable, porous, calcareous sandy clay loam, with no peds and no clay faces—in fact, a typical C horizon condition for Speewa soils. However, in passing to the transect represented by profile 2 the various horizons of the Speewa disappear consecutively from the upper to the lower, until finally only material with typical C horizon fabric and properties dominating remains. This situation, involving a vertical elimination of the soil horizons, is taken as evidence of the unconformable truncation of a previously developed soil. It is argued that neither the gradation of A horizon characteristics to B horizon characteristics nor the gradation of B horizon characteristics to C horizon characteristics could have come into existence without there having been at one time a full ABC horizon organization represented

now by its incomplete parts. However, since the full implications of the assumptions may not be acceptable without reservations, the argument is restricted here to those cases (as in Figs. 2 and 3) where the various parts of the soil layer, the complete profiles and the part-soils, are shown to be physically continuous, and with no suggestions of breaks or discontinuities in either the horizontal or vertical axis.

On the basis of the foregoing argument, it is concluded that data of the type contained in Figs. 2 and 3 provide evidence that the soil layers were subject to variable erosion after soil development on them. Later events lead to the deposition of another layer. The result is the occurrence of buried part-soils, and Fig. 2 indicates that the upper soil system—in this case the Kyalite, though the same principle applies for any layer—may overlie the A, B, Bca, or C horizon of the lower soil. More detailed descriptions to be published elsewhere (Churchward, 1960*a*) show that the occurrence of buried part-soils involving all of the soil layers is quite common in the Swan Hill area. Vertical sequences involving three or more superposed, but partly truncated soils are common: and horizon assemblages such as the following occur:

(uppermost soil//B, Bca, C of 2nd soil//B, Bca, C of 3rd soil);
(uppermost soil//Bca, C of 2nd soil//Bca, C of 3rd soil);
(uppermost soil//Bca of 2nd soil//Bca of 3rd soil).

It will be inferred that the possible variety of horizon assemblages is very wide, and that the possible horizon superpositions are pedologically random.

VII. *Discussion*

The general occurrence of buried soil systems entails an alternation in the history of the region between soil-forming periods, and periods of erosion and deposition. The general outline of the situation is discussed by Butler (1959).

It is seen that certain deceptive genetic relationships are commonplace in the profiles at Swan Hill. These are the result of the random association of the several horizons of separate soil profiles from different ground-surfaces. The random element has given rise to pedogenetically unfeasible situations. For instance, the superposition of Bca horizons on A or B horizon material, is a situation which is particularly common in the materials of the aeolian landscape. Furthermore, with riverine layers, the least weathered Coonambidgal materials are superimposed on a recurrent sequence of variably weathered zones.

Perhaps the main significance of the present study is the conclusion that many of the profile assemblages in the locality are not single pedogenic units, but consist of pedogenetically independent layers; incomplete, or part-soils, are represented in the superposed layers as well as complete, single-system, pedogenetic assemblages. The task of sorting out these complications, or proving the several single systems of which the whole is composed, and of selecting suitable examples of them for further pedologic study, requires the stratigraphic type of study outlined above.

The conclusions arrived at in this study have implications for the general study of the brown solonized Mallee group of soils (Prescott, 1931), because the general soil conditions, as well as the associated landscape, climate, and vegetation of the Swan Hill area, are fairly representative of the group. Previous studies of these soils (Prescott and Piper, 1932; Northcote, 1951, 1956) have not clearly established that the samples used come from single-system profiles. Northcote (1951, 1956) has proposed a halomorphic succession to explain the array of soil morphological features in the Coomealla area. It is considered that its similarity and proximity to the Swan Hill area would suggest comparable factors govern the soils and landscape. Indeed, the general stratigraphic situation at Coomealla (as described by Northcote, 1951), showing an acid clay substratum beneath a sandy and calcareous material having considerable variability, has a parallel in the aeolian landscape at Swan Hill. However, any attempt to apply the above succession to explain similar soil morphologies in the Swan Hill locality is thwarted by their complexity, this being a reflection of geomorphic history rather than pedologic processes.

At Swan Hill it was found that the soils showing the range of morphological features encompassed by Northcote's halomorphic sequence are frequently compounded of elements of more than one layer. For instance, those of the 'solonetzous-solodous group' frequently show a non-calcareous Kyalite sand overlying a range of profiles for the Speewa layer which show little or no truncation. Such a complex profile arrangement is seen in profile 1 of Fig. 2. On the other hand, the 'solonchakous group' is represented by the fine-textured, more calcareous Kyalite profile over severely truncated Speewa profiles. It will be seen, therefore, that profiles of the first group have resulted by the juxtaposition of at least two layers of material having strikingly different clay and lime contents. On the other hand, the latter group could well be due to the burial of one layer (frequently severely truncated) by material showing similar textures and fine-earth lime content, and hence resulting in a compound profile showing little texture variation. This variable superposition of materials could also explain the occurrence of the clay maxima *above* the lime maxima, or the association of the clay maxima *with* the lime maxima of some of the profiles reported for Coomealla (Northcote, 1951). The single profiles of the Swan Hill district, where these are proved by stratigraphic means, show a relatively marked clay maximum. In compound profile assemblages, however, the apparent contrast of the B horizon would depend on the degree of truncation of the buried soil, and the texture of the burying layer.

It is concluded that a study of variation in soil materials with the particular objective of distinguishing variation within layers from variation between layers, can be very useful. The technique of tracing the lateral continuity of a proposed layer across a diversity of substrata proves the separateness of the layer. At Swan Hill it is found that the remaining variation within soil layers is orderly with consistent waxing and waning trends down the vertical axis such as is normally accepted as pedogenetic.

VIII. *Acknowledgements*

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PROBLEMS OF SOIL EVALUATION IN THE SUDAN

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Summary

The present soil evaluation of alluvial clay plains in the Sudan is a selective land classification for cotton cultivation under irrigation and based mainly on the sodium-value concept. This Na-value, being a corrected Na-figure (Na:clay ratio), was developed and used for pre-estimations of cotton yield levels. It is now shown that owing to its similarity with the exchangeable-sodium-percentage concept and to the fact that it does not generally give a satisfactory yield correlation the Na-value has in practice been useful only for the exclusion of sodic soils.

Re-examination of the Na-value concept reveals that, instead of sodium value the clay content is a superior criterion for yield estimations. Cotton yield levels are positively correlated with clay contents of 40–70 per cent. A new clay-yield formula, $Y = -49{\cdot}3 + 2{\cdot}57X$, where Y = per cent. relative yield and X = per cent. clay content of the 0–40-cm. layer, has been developed as a preliminary basis for the evaluation of cotton soils.

Introduction

WHEN large-scale cotton production under irrigation started about 1920 in the Sudan, suitable soils were selected according to salt contents, i.e. salty areas were excluded (Joseph, 1925). This mode of selection, however, did not always give satisfactory results, and several attempts were made to correlate cotton yields with other soil characteristics such as profile morphology (Whitfeild, 1935), sodium uptake, capillary rise, &c. Finally, soil evaluation was based on the sodium content which, as a corrected value, became the main criterion (Snow, 1941).

A recent productivity study of the Gezira has cast doubt on the dominance of the sodium content as a yield-determining factor and has drawn attention to the clay content as being probably a superior one (Finck, 1959). Extensive examination of these two concepts led to this paper, in which the present system of soil evaluation is described and the results of the examination of the alternative—clay versus sodium content as a basis for soil evaluation—are presented. Outlines of an improved system are put forward.

Because the yields of the large uniform Gezira Scheme are recorded in detail, it offers a unique opportunity for a calibration of yield-determining factors. The results obtained may be applicable not only to other arid clay plains in the Sudan, but also to similar areas elsewhere.

The Present System of Soil Evaluation

The Sodium Value

The main criterion of the present system is the 'sodium value', developed by Snow in 1941. He found at the small Dueim Pump Scheme (White Nile area) a good correlation between the Na:clay ratio of the 0–90-cm. layer of the soil and the cotton yield levels, i.e. average

relative yields in per cent. Both soluble and exchangeable sodium were determined and the total expressed in milliequivalents per 100 g. of oven-dry clay. The value obtained was called the 'sodium value', and was to be used as a criterion for the selection of soils with good-quality clay (Snow, 1941). The sodium contents were corrected by the clay contents (as a substitute for the cation-exchange capacity) because the effect from an adsorbed quantity of sodium would be inversely proportional to the clay content.

The Na-value concept was tested further in the large Gezira Scheme area, the soil of which is of Blue Nile origin. The results of all tests

TABLE 1

The Basis of the Na-value Concept

Area	*n*	*Regression coefficient b*	*Coefficient of determination* r^2 (%)
1. Dueim Pump Scheme . . .	32	$-2{\cdot}71^{xxx}$	$49{\cdot}9^{xxx}$
2. Gezira, 33 Blocks	33	$-0{\cdot}19^{NS}$	$0{\cdot}6^{NS}$
3. Gezira, 99 Record Areas . . .	99	—	$7{\cdot}1^{xx}$
3a. Gezira, 48 Record Areas . . .	48	$-1{\cdot}05^{x}$	$10{\cdot}4^{x}$

(*a*) Variables: *Y*, rel. cotton yield in per cent. of respective area (average of several years); *X*, Na-value of the soil layer 0–90 cm.
(*b*) The original data of the 48 Record Areas were obtained by averaging similar data from contiguous members of 99 sub-plots.
(*c*) Significance levels (per cent.): xxx, $P < 0{\cdot}1$; xx, $P < 1$; x, $P < 5$; NS, $P > 5$.

carried out are compiled in Table 1. They are obtained from Jewitt (1955) and the unpublished manuscripts of Snow (1941, 1942), checked and partly transformed in order to make the regression coefficients comparable. These data show that the Na-value has a reasonable basis at Dueim where it was originally developed. Although the yield correlation in the Gezira was not as satisfactory as at Dueim it was considered to be sufficiently significant to allow for a wide application (Snow, 1942). The Na-value formula developed at Dueim:

$$Y = 162{\cdot}6 - 2{\cdot}7X$$

(where Y = relative yield in per cent. and X = Na-value) by means of which estimates of yield could be made, was accepted as the basis of soil evaluation. 'The Na-test, by its very nature must measure or stress the basic value of the soil' (Snow, 1941). According to the formula a scale of limiting values was calculated with reference to which areas were classified as to their suitability for cotton cultivation (see Table 2). Those with Na-values over 35 (less than 70 per cent. rel. yield) were to be excluded.

The originator of the Na-value concept was well aware of its limitations. He considered it as being of a preliminary nature, and restricted its applicability to areas similar to Dueim or the Gezira Scheme. Even

within these alluvial areas he insisted on additional limitations, e.g. the Na-value was not to be applied to sandy or exhausted soils, or to soils in a rainless climate, &c. In course of time, however, these limitations have been more and more disregarded.

The Evaluation of Soils

From 1942 until about 1958 new areas proposed for irrigation were selected according to the criteria presented in Table 2. Since the limitations of a low clay and a high salt content occurred only occasionally, the soil evaluation was in fact based mainly on the Na-value.

TABLE 2

Soil Evaluation System of Sudan Arid Clay Plains

(Data refer to the 0–90-cm. soil layer)

Class	*Na-value*	*Clay* (%)	*Salt* (%)
I. Good	0–25	> 40	< 0·3
II. Medium	26–35	> 35	< 0·5
III. Bad	> 35	< 35	> 0·5

Areas which fell under class III were to be excluded from cotton cultivation. The determinations of sodium and clay contents were carried out on composite samples of the top 3 ft. of the soil. In addition, a description was made of each foot deep layer of the profile down to 6 ft. (1·83 m.). Samples of each layer were taken and analysed for salt content and pH. Other chemical data such as carbonate and organic carbon and nitrogen contents were frequently determined, but not used for soil evaluation. For soil sampling, pits were dug at regular intervals in a grid pattern. The density of these varied according to local conditions from one pit per 40 ha. to one per 1,200 ha. In 1958 Ochtman (1960) modified this classification by (*a*) taking into account morphological and topographical features, (*b*) setting limits for the salt content of the first foot, e.g. 0·15 per cent. for good soil, and (*c*) adding a sub-division to class III with Na-values from 35 to 45 called 'passable, but generally to be excluded'. In addition, the soils of new areas were described and sampled according to soil horizons. Despite these modifications, doubts have recently been expressed as to whether the Na-value is really the appropriate concept for the evaluation of these soils. In practice, more than once it was shown that, although in general the system worked quite satisfactorily, the level of fertility had been greatly overestimated; so-called 'medium' soils produced only very poor yields. In theory, it was pointed out by the present authors in 1958 that for the Gezira the yield correlation of the Na-value was rather low (only up to 10 per cent., see Table 1). The data therefore seemed to be more in favour of the opposite conclusion, i.e. that the Na-value is not a satisfactory concept for soil evaluation. Furthermore it seemed to be questionable whether the Na-value, being (as will be shown later) very similar to

the 'exchangeable-sodium-percentage' concept, could really be a good criterion for yield estimations on non-sodic soils. Toms (1960), having re-examined from older data the yield Na-value relation for 36 Gezira Blocks and finding a coefficient of determination of only 18 per cent., also regarded the correlation as unsatisfactory.

A re-examination of the present soil evaluation system, especially of the Na-value concept as the main criterion, therefore seemed to be necessary.

Na-value versus other Concepts

The discussion on the Na-value has two different aspects, which should be clearly distinguished. First, there is the original use of this concept for soil evaluation, and secondly, its usefulness for the exclusion of sodic soil without any evaluation of the land selected. Unfortunately, these aspects have not been separated in the past.

Soil Evaluation Concepts

According to Snow the major factor accounting for local yield variations of cotton on Sudan alluvial soils is the Na-value. On re-examination, however, the clay content appeared to be a superior criterion of soil evaluation. In order to examine this alternative, the original data from which the Na-value concept was derived, were re-examined and the individual factors calculated separately (Finck, 1960). The results are compared with those of the recent productivity study (Tables 3 and 4).

TABLE 3

Regression Data of Cotton Yields on Clay and Na-content

Area	*n*	*Range* Y / X_1 / X_2	*Simple regression*			*Partial regression*	
			b_{y1}	b_{y2}	*a for* b_{y1}	$b_{y1.2}$	$b_{y2.1}$
1. Dueim Pump Scheme	32	37–205 300–840 1·45–5·08	0·355^{xxx}	−22·99^{xxx}	−106·6	0·303^{xxx}	−8·97^{NS}
2. Gezira, 33 Blocks .	33	87–119 480–650 1·91–3·24	0·118^{xxx}	+ 4·99^{NS}	+33·5	0·123^{xxx}	+6·44^{x}
3. Gezira, 48 Plots .	48	65–153 420–650 1·36–3·59	0·190^{xxx}	−4·36^{NS}	−5·97	0·216^{xxx}	+5·84^{NS}
4. Gezira Prod. Study 58/59	15	66–122 440–690 0·39–2·39	0·226^{xxx}	−26·64^{xxx}	−35·2	0·216^{xxx}	−1·47^{NS}

Variables: Y, relat. cotton yield in per cent. (mean of several seasons; actual yield approx. 0·4 —1t./ha. lint); X_1 (= 1), clay content per thousand; X_2 (= 2), content of solub. plus exchang. Na per thousand.
Data of areas 1, 2, 3, refer to the 0–90-cm. layer, those of area 4 to the 0–35-cm. layer.
Significance: see Table 1.

From these data it is evident that yield is mainly associated with the clay content of the soil. The Na-content alone seems to have hardly any influence on the yield variation, provided that such conclusions may be

drawn from statistics. This result is not unexpected if the original Na-data are considered. They are generally below the level at which an adverse effect due to sodium can be anticipated.

Clay contents ranging from 40–70 per cent. are positively associated with relative cotton yields. This result does not agree with the general belief that deeply pervious loams are nearly ideal for irrigation (Storie, 1933; Kellogg, 1956). Similarly, in the Sudan, although previously it was generally agreed that soils with a clay content below 40 per cent. were less suitable for cotton, it was considered that the high clay content of the Gezira soil (in addition to its exchangeable sodium content of 8–12 per cent.) was a cause of its low permeability (Crowther, 1952).

TABLE 4

Correlation Data of the Relation between Cotton Yield and Clay and Na-content

Area	*Simple correlation*			*Partial correlation*		*Multiple correlation*
	r^2_{y1} (%)	r^2_{y2} (%)	r^2_{12} (%)	$r_{y1.2}$	$r_{y2.1}$	R^2_{y12} (%)
1. Dueim Pump Scheme .	$68{\cdot}5^{xxx}$	$(-)36{\cdot}0^{xxx}$	$(-)26{\cdot}8^{xx}$	$0{\cdot}755^{xxx}$	$-0{\cdot}357^{x}$	$72{\cdot}5^{xxx}$
2. Gezira, 33 Blocks .	$38{\cdot}3^{xxx}$	$+5{\cdot}2^{NS}$	$(-)1{\cdot}0^{NS}$	$0{\cdot}663^{xxx}$	$+0{\cdot}371^{x}$	$46{\cdot}8^{xxx}$
3. Gezira, 48 Plots . .	$33{\cdot}9^{xxx}$	$(-)1{\cdot}7^{NS}$	$(-)20{\cdot}9^{xx}$	$0{\cdot}593^{xxx}$	$+0{\cdot}189^{NS}$	$36{\cdot}2^{xxx}$
4. Gezira Prod. Study .	$86{\cdot}9^{xxx}$	$(-)66{\cdot}5^{xxx}$	$(-)74{\cdot}4^{xxx}$	$0{\cdot}778^{xxx}$	$-0{\cdot}064^{NS}$	$86{\cdot}9^{xxx}$

Legend: see Table 3. The (−) sign indicates negative correlation.

Low permeability, interfering with root growth and water supply of the plants, is an important cause of low fertility according to Greene (1939). Some of the highly productive areas of Egypt, however, are examples of soils with a high clay content which are permeable, perfectly amenable to cultivation and favourable to plant growth (Means, cited by Beam, 1911).

The agreement between the regressions of the three completely different sets of samples is striking (see also Fig. 3). Over the whole range the relation between clay and yield seems to have an inclined sigmoid shape, the central part of the curves (presented in the figures) being fairly linear.

The clay content has not only a higher yield association than the Na-content, but its yield correlation is also superior to that of the Na-value, as a comparison of Figs. 1 and 2 with the Dueim data reveals.

The superiority of the clay content is further illustrated by the following Table 5. The Na-value concept failed to explain three major discrepancies at the Dueim Scheme, whereas the clay content gives a satisfactory correlation with the yields.

In two out of these three cases the estimation via clay comes very close to the actual yield level.

Using the clay content as a yardstick for soil evaluation is not only simple, but avoids also the difficulty of a correction of the Na-content, which decreases if land becomes cultivated.

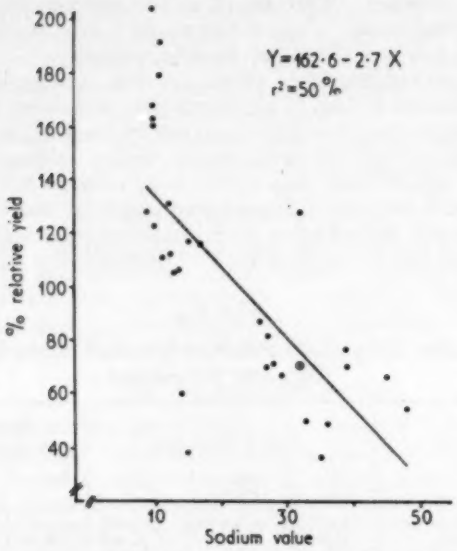

FIG. 1. Association between yield and Na-value at Dueim Scheme.

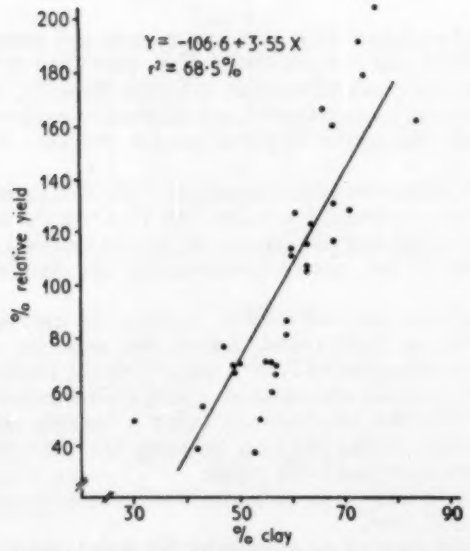

FIG. 2. Association between yield and clay content at Dueim Scheme.

The causal relation underlying this clay-yield association has not yet been studied. There is the possibility, however, that since the permeability of the Ca-montmorillonitic surface layers of this 'Gezira Clay' soil depends to a large extent on the formation of cracks, a higher clay content resulting in more extensive cracking might increase the permeability.

TABLE 5

Comparison of Yield Estimations from the Na-value and Clay Content at Dueim Pump Scheme

	Soil data		*Measured relative yield* (%)	*Estimated yields in* (%)	
Plot	*Clay* (%)	*Na-value*		*from Na-value*	*from clay*
23	61	32	128	76	110
16	56	14	60	125	92
101	42	15	39	122	43

Concepts for the Exclusion of Sodic Soils

According to its design the Na-value is useful for the exclusion of sodic soils. Provided that the cation exchange capacity of the clay of the areas investigated is uniform, the Na-value concept is very similar to that of the widely accepted 'exchangeable-sodium-percentage' (ESP), except for the fact that the Na-value includes the soluble sodium.

In the Gezira the clay (being mainly montmorillonitic) has a cation exchange capacity of one milliequivalent per gramme (Jewitt, 1955). If one assumes that 50 per cent. of the sodium is exchangeable, a Na-value of 30 would correspond to 15 per cent. ESP, which is the accepted limit for sodic soil; the depths compared, however, are not equal. If one assumes one-third of the sodium to be exchangeable, a Na-value of 45 corresponds to 15 per cent. ESP.

The use of the Na-value for the exclusion of sodic soil does not necessarily require a yield calibration under all local circumstances, because it is based on accepted experience. The Na-value, although not developed for this restricted purpose, has in practice been useful mainly in this respect. It thus has its merits and could be used in future.

One has, however, to consider whether the original concept in all details, e.g. sampling of the 0–90-cm. layer, should be retained or modified. It might also be replaced by the widely accepted ESP concept.

Outlines of an Improved System

In addition to the exclusion of chemically and physically unsuitable areas and, if possible, the indication of reclamation possibilities, the evaluation of the land not excluded is necessary. From former and recent investigations it is possible to suggest some outlines for a new soil evaluation concept with regard to cotton cultivation on alluvial clay plains similar to the Gezira.

Since the clay content has proved to be a useful criterion for yield estimations in several investigations, a soil evaluation formula on the

basis of the clay content can be developed. For further improvement the inclusion of other factors, e.g. organic matter, nitrogen, &c., is under consideration. It is now suggested that a clay-yield formula should be constructed as the arithmetic mean of the regressions of the three most conclusive investigations available, i.e. those of Dueim, of the 48 Record Areas, and of the recent productivity study of the Gezira, thus disregarding the different number of samples and giving the Gezira data twice the importance of the Dueim data.

Since the regression coefficients are significant and their confidence intervals overlap and since the three r-values have almost a common

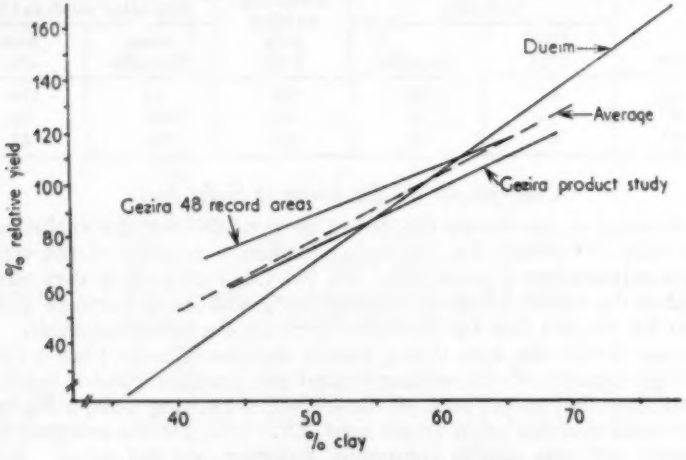

FIG. 3. Regressions of yields on clay contents.

population correlation coefficient, one might be entitled to average these three regressions in a new clay-yield formula:

$$Y = -49{\cdot}3 + 2{\cdot}57\,X,$$

Where Y = per cent. relative yield and X = per cent. clay content of the 0–30/40-cm. layer. This formula has an r^2 value of approximately 55 per cent. and is valid within the range for X from 40 to 70 per cent. A relative yield of 100 per cent. corresponds with a clay content of 58 per cent. Fig. 3 gives the original three regressions with the new average one.

Of course the validity of this clay-yield relationship is restricted to soils similar to those of the Gezira, i.e. alkaline, montmorillonitic clay soils in a hot and dry climate, under conditions of similar management, &c.

In the Sudan, as elsewhere, soil selection for one cash crop is not the ultimate goal of soil evaluation. Crops other than cotton have to be considered. Soils other than those of the clay plains hitherto investigated will have to be evaluated. The diversity of soils in the Sudan is very great ranging from leached latosols and swamps to desert soils.

At present there are two large projects under consideration: the survey of the Kenana area (12,000 km.^{2}) and of the Equatoria Province (200,000 km.^{2}). Since new areas will no longer be developed exclusively for large-scale cotton cultivation, a general land use capability classification becomes necessary. Following international experience, a map of the taxonomic soil units will be the basis of this method of classification. For other crops and soils, work along the lines already developed for cotton on alluvial soils, will be attempted.

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SOME MISCONCEPTIONS ABOUT WHAT SOIL SURVEYS CAN DO[1]

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Summary

The soil-classification system used for a soil survey is fundamental to the success of the survey, and, if it is to be a valuable system, its nature must be determined by the purposes of the survey.

The idea of a soil-classification system which may be applied generally is valid only if the criteria required for different purposes are similar or correlate closely. Examples of surveys from Australia discredit the idea on the grounds that the soil criteria to be used in the classification differ according to the purposes of the surveys.

Soil surveys based on a supposedly general-purpose classification may thus be strictly limited in value, as they often do not make assessments of soil properties that are significant for different purposes. This is particularly so when one classification is used over a wide range of environment.

Two approaches may help to make surveys more valuable. One is to devise an improved approximation to a general-purpose classification by selecting better key criteria, and to ameliorate its deficiencies by incorporating it into an ecosystem survey. The other is to adopt a specialist classification for each different purpose of survey. Both approaches have their limitations.

In the long run soil surveys are simply a means of assessing one factor amongst others in a landscape which is being studied or used. This is done by grouping together the soils which are similar for the purpose in hand, separating them from other soils, and showing their distribution. The value of a soil survey, then, depends primarily on the way in which the soils are grouped—that is to say, on the classification of the soils of the area surveyed.

A classification of anything is a certain arrangement of particular interval groupings of selected criteria. Therefore, variations in the classification are possible at three different levels, namely, the criteria selected, the interval groupings adopted of those criteria, and the arrangement of the interval groupings. Let us examine the position, as far as soils are concerned, for the first level, that of criteria.

How many criteria are there for soils? Those few commonly used, such as colour, texture, structure, and consistency, all down the profile, with carbonate and gypsum if present, are certainly valid criteria. However, there are many others, which could be used if desired, such as the size distribution of humus particles, the ability of the soil to reflect any wavelength one may care to name outside the visible spectrum, or the number of bacteria per gramme of soil. Valid criteria are even those which at one time may appear foolish, such as the content of zircon or zinc, or the number of crystals of gorceixite of a particular shape, but

[1] The criticisms of Mr. R. G. Downes, Soil Conservation Authority of Victoria, are gratefully acknowledged.

which later may be found of some importance. Indeed, the list of 'valid' criteria could be extended *ad infinitum*.

However, a classification cannot be devised with an infinite number of criteria, so that a selection of a few must be made. Upon what basis do we select? Clearly, it is for some purpose, as otherwise we would not select at all—but for which purpose?

We could select criteria which would separate soils of varying suitability for growing lucerne in a hot dry climate—if we knew what criteria were important for growing lucerne in a hot dry climate; we could select criteria having in mind the growing of pines in a cold wet climate—if we knew the criteria for such an enterprise. We could even select criteria of value for building foundations, then make our classification and start mapping on that basis. Provided that the criteria important for each of these purposes were known, we could make excellent and useful classifications, and, if the soils classified on the basis of those criteria were mappable, then maps also, along those lines.

It would be fatuous, however, to think that any one of these classifications could serve the other purposes unless the criteria are identical for each purpose, or are at least very closely correlated.

Here are some examples to show how the significance of the chief criteria may vary according to the purpose for which the soils are being examined and how the correlations are sometimes very weak.

(*a*) The suitability of soils for growing clover in a 25-inch rainfall in western Victoria, after the addition of superphosphate, depends chiefly on how long into the dry summer the soils have the ability to supply water to the shallow root system, and on the levels of potassium, copper, molybdenum, and pH. Each of these properties may be a limiting factor. For soils with a light-textured surface, the water-supplying ability resolves itself into a matter of the depth of an impeding horizon which is determined by the texture profile or hardpan profile; however, this is altered by a change in environment as under certain topographic conditions the soil may be suitable regardless of the texture profile (Gibbons and Mitchell 1956).

(*b*) The chief soil feature needed for growing pines in the same area is adequate aeration, and on soils satisfying this requirement, possible principal limiting factors for pines are the elements phosphorus and calcium. Criteria to be accounted for in a survey for this purpose, then, are the texture profile, structure profile, phosphorus, and calcium.

(*c*) After phosphate is added, wheat-growing in the Victorian Mallee is largely a matter of the ability of the soil to store and yield to the plant the water falling during the growing period—that is, a question of the organic-matter content and texture of the surface soil—and to provide nitrogen, which is limiting to various degrees (Rowan, 1958). On the other hand, wheat-growing in north-western New South Wales is most successful on a soil which can store the water of the previous late summer (Hallsworth *et al.*, 1954; Waring *et al.*, 1958). This is a matter of the quantity, type, and cation-exchange characters of the subsoil clay. Phosphorus may or may not be limiting.

(*d*) One of the important features of soils as base material for building

foundations is the resistance to deformation, both due to seasonal influences and under applied loads. Whereas, theoretically, this resistance is a function of the quantity, type, and cation-exchange characters of the clay, and of the structure, in practice the classes commonly used for expressing texture, and the criteria used for expressing structure, show very little correlation with the deformation characteristics in the southern States of Australia (Aitchison, priv. comm.).

(*e*) The value of soils in the water-supplying powers of a catchment in the high mountains of Gippsland is chiefly determined by the infiltration capacity, the erosion resistance, and the hydraulic conductivity. The first is controlled by surface sealing and also profile restriction which is a matter of the texture and structure profiles. The erosion resistance is partly controlled by the drag-force resistance, which, with the hydraulic conductivity, is theoretically referable to the texture and structure profiles, but the directly determined values of which may show little accord with such theoretical correlations (Turner, 1960; Childs *et al.*, 1957).

From these examples, two things may be noticed. Firstly, of eighteen soil criteria listed, only two (texture profile and structure profile) are common to most of the purposes, whilst the remaining sixteen are individually restricted to only a selection of the examples. That is to say, the criteria selected are not identical for different purposes, nor for the same purpose under different environments. Secondly, only five of the listed criteria (texture profile, structure profile, hardpan profile, cation-exchange characters, and pH) are adopted in any of the existing or proposed classifications commonly used in Victoria.[1] Admittedly the most frequently needed criteria (texture and structure profiles) are among these. However, of the thirteen remaining criteria not used, only three (K, Cu, and lime requirement) show any consistent close correlation with any criteria used in those classifications, three (Zn, Mo, and clay type) show a doubtful correlation, and seven (P, N, organic matter, deformation resistance, surface sealing, drag-force resistance, and hydraulic conductivity) show no consistent close correlation.

This analysis comes from only five circumstances selected at random, mostly in one State. Undoubtedly, the number of criteria needed could be multiplied by more examples.

I am forced to the conclusion—reluctantly, because my own surveying activities are thereby criticized, just as much as those of anyone else—that a universally applicable, or General-Purpose classification does not exist. Nor, on theoretical grounds, do I think that it *can* exist, either for the same purpose in different environments, or for different purposes in the same environment, and still less for different purposes in different environments. Moreover, we can only map what is mappable, so that to produce a map requires a classification in which the criteria are those stimulating response from the unaided human senses only. Thus, we do not always use the criteria that are needed. The heart of the problem, however, is rather that those criteria which *are* needed are often the hidden, unmappable features whose correlations are frequently not

[1] C. G. Stephens's classification; U.S.D.A. (Guy Smith's) 5th approximation; Hallsworth, Costin, and Gibbons (1953).

known with those criteria, which, since they are to be used, are necessarily restricted to those upon whose basis the soils can be mapped.

There seem to be two courses out of this situation. The one is to do the best we can in the way of a General Purpose classification by attempting to find visual key criteria which correlate with most of the criteria, visual and analytical, which we deem important for most foreseeable purposes, and to use this classification, together with other features of the environment, in a mapping programme. This use of the other environmental variables such as climate, geology, topography, and vegetation, by defining and describing the components of the ecosystem (e.g. Costin, 1954; Christian and Stewart, 1947) is more likely to achieve the varied purposes of a soil survey than would the soil survey alone. This it can do because it takes cognisance of other independent factors which influence plant growth, and also uses a dependent variable, vegetation, which may reflect the hidden, unmappable soil properties, which are significant for plant growth. In suggesting this course, the limitations of such an ecosystem approach are realized, and have been pointed out, in part and perhaps with undue severity, by Butler (1957).

The other course is to devise specialist classifications for known purposes over limited areas, and map accordingly. In fact, this might be the best for any detailed investigation, whether or not a General-Purpose approach has been used regionally in the initial stages to decide the most suitable enterprise for further consideration.

This course presupposes, however, that the chief relevant criteria are known and the soil units based on them are mappable; if they are not, then there is little point in doing any survey at all on the basis of possibly irrelevant criteria simply because the soils based on them are mappable. The chief need in such a case is rather to seek the correlation between the criterion upon whose basis the soils can be mapped, and that which is relevant to land use. This may involve one or more intermediate parameters, such as, for instance, the phosphate-sorption value proposed by Colwell (1959) in his attempts to relate soil units to phosphate responses in wheat. Indeed, the position has probably been reached where some surveys must await the further researches of the soil chemist.

So far, this criticism has been only on the first level mentioned earlier, that of the selection of criteria. No mention has been made of the second level, the interval grouping of the criteria, and whilst there is no intention of embarking upon a criticism of the whole concept of the General-Purpose classification at that second level, there is no doubt that it offers plenty of opportunity to do so.

Sometimes we hear arguments that if the classification be sufficiently detailed, the required information for any purpose—that is, a specialist classification—can be devised by a rearrangement of existing classification units. This is true only where the inadequacy is at the second level —the group intervals adopted. However, if the criteria chosen do not include those pertinent to the case, then no amount of rearranging or selecting of group intervals can resolve the difficulty.

The principles developed in this paper may be applied to any scheme

to map the soils on a continental scale on the basis of one General-Purpose classification. In Australia such a scheme would mean an attempt to map soils which will be used for very many different purposes in environments ranging from antarctic-alpine through wet tropical to hot desert, using criteria selected for a purpose and an environment which we do not yet know.

It would be quite unfair to say that useful information would not come out of such an attempt, for a General-Purpose classification uses some criteria which may be shown to be of importance for a number of purposes. If we realize the limits imposed by whatever few criteria are chosen, and understand that we are collecting limited information of uncertain significance for a multitude of purposes as yet unknown, then let us go right ahead.

However, if it be thought that the classification units so mapped bear any intrinsic relationship to the eventual use of the soil, or that the mere superposition of climatic, topographic, and economic data would complete our requirements for planning, or even that the survey has some objectively fundamental character, then our hopes will be falsely based on unsound principles.

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MECHANICAL COMPOSITION OF SOLODIZED SOLONETZ AND SOLONETZ-LIKE[1] SOILS OF SASKATCHEWAN[2]

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Summary

Median values of pH, conductivity, organic and inorganic carbon, and mechanical analyses are reported for nine solodized solonetz soils and eight solonetz-like soils. These data show that for solodized solonetz soils the A horizons are moderately acid, with the A_2 and A_3 horizons showing the greatest acidity. The B_1 is neutral, and the lower B and C horizons are alkaline in reaction. The solonetz-like profiles show a similar trend, but pH values are higher in the A horizons. Conductivity rises progressively from the A_1 horizon downward in the solodized solonetz group, whereas in the solonetz-like group the conductivity remains very low throughout.

A regional Dark Brown prismatic profile is included for comparison.

A PREVIOUS paper (Janzen and Moss, 1956) presented data on exchangeable cations, pH, and conductivity of solodized solonetz and solonetz-like soils of Saskatchewan. The present paper deals chiefly with the mechanical composition of the above soils, together with information on several additional profiles. Data for pH and conductivity and organic and inorganic carbon are also reported.

The main objectives of the study were:

(1) To confirm the field evidence of clay accumulation in the upper B horizons of solonetzic soils.
(2) To compare the mechanical composition of solodized solonetz and solonetz-like soils, in view of the evidence from previous studies that the latter soils show less solonetzic development.
(3) To compare the mechanical composition of solonetzic soils from widely separated locations within the Grassland Region of Saskatchewan, ranging from the semi-arid section of the southern portion to the sub-humid section of the northern limit of the Region (Brown to Black Soil Zones).

Solodized solonetz soils are characterized by a leached A horizon, including a well-developed, light-coloured A_2 horizon. The B horizon is columnar-structured, with whitish coloured rounded tops, and surface coatings and organic staining on the sides of the columns. The B horizon is very hard when dry and is finer-textured than the A. The parent material is saline.

The solonetz-like soils usually lack an A_2 horizon or if present it is very thin. The B horizon is prismatic to faintly columnar, finer-textured than the A horizon, but less hard and compact than the B horizon of the

[1] The profile type referred to as 'solonetz-like' in this paper is designated as 'solonetz' by the National Soil Survey Committee (Canada).

[2] Contribution No. 58, Canada Department of Agriculture Research Station, Saskatoon, Sask., in collaboration with the Saskatchewan Soil Survey.

solodized solonetz. The C horizon of the solonetz-like soil is usually much less saline than is that of the solodized solonetz types.

Methods of Analyses

pH and conductivity were determined by the saturated paste method as outlined by the U.S. Regional Salinity Laboratory (1954).

Organic carbon was done by the dry combustion method, absorbing the evolved CO_2 in standard NaOH and back titrating the excess base with standard HCl.

Inorganic carbon[1] was determined by boiling the sample in 2N HCl, absorbing the evolved CO_2 in standard NaOH, and back titrating the excess base with standard HCl.[2] Inorganic carbon, including that portion combined as dolomite, is then calculated to the $CaCO_3$ equivalent.

The procedure for mechanical analyses, a modification of the Kilmer–Alexander method (1949), consisted essentially of treating the soil sample with N HCl in the cold to destroy the carbonates in calcareous samples. The pH of the calcareous, as well as the non-calcareous samples, was finally reduced to pH 4·5–4·0 using Brom Cresol Green indicator. The sample was then washed free of the water-soluble and acid-soluble material. After treatment with 30 per cent. hydrogen peroxide to destroy organic matter, the sample was dispersed by shaking for 12 to 16 hours on an end-over-end shaker, using Calgon (sodium hexametaphosphate) as dispersing agent. The sands (greater than 50 μ) were then sieved off, dried, and weighed, the silt and clay being determined by the pipette method. Fine clay (less than 0·125 μ) was determined by a combination of centrifuge and pipette. All results are reported on a carbonate-free, organic matter-free, oven-dry weight basis.

Results

Median values for mechanical analyses, pH, conductivity, and organic and inorganic carbon for nine solodized solonetz profiles are presented in Table 1. This table shows:

1. A marked increase in total silt and a decrease in total clay of the A horizon as compared with the B and C horizons. Thus, the A_2 horizon contains approximately 50 per cent. more silt and 45 per cent. less clay than the C horizon.

2. In the silt fractions, the greatest increases occur in the coarse silt (50–20 μ), the A horizons containing about 60 per cent. more silt than the B_1 horizon, and twice as much as the lower B and C horizons. The increase in medium silt (20–5 μ) is somewhat less, the increase ranging from 40 per cent. in the A_2 horizon to about 55 per cent. in the A_1 as compared with the lower B and C horizons. For the fine silt fraction (5–2 μ) there is actually a slight decrease in the A horizons as compared

[1] Includes dolomitic limestone or dolomite which may be present.

[2] $SnCl_2$ was used as an antioxidant to reduce decarboxylation of organic matter. The recovery of very small but measurable amounts of inorganic carbon from relatively acid, organic matter-containing horizons would indicate the above treatment does not completely eliminate the decarboxylation process (see Tables 1 and 2).

TABLE 1

Median Values of Analyses of Nine Solodized Solonetz Soils

Horizon	pH	Conductivity (mmhos/cm.)	Organic carbon	Inorganic carbon	Mechanical analyses						
					Total sand greater than 50 μ	Total silt 50–2 μ	Coarse silt 50–20 μ	Medium silt 20–5 μ	Fine silt 5–2 μ	Total clay less than 2 μ	Fine clay less than 0·125 μ
A_1	5·7	0·3	3·37	0·02	37·3	39·2	14·2	18·0	6·9	23·0	11·0
A_2	5·4	0·4	1·37	0·01	39·1	37·7	16·0	16·3	5·5	18·5	8·9
A_3•	5·3	0·5	0·72	0·01	53·9	32·2	15·7	11·8	4·6	11·8	4·7
B_1	6·9	1·8	1·28	0·01	31·5	27·7	9·5	11·5	6·7	43·0	25·0
B_2	8·2	2·5	0·56	0·72	41·9	25·7	7·8	10·7	7·2	31·7	17·1
B_3†	8·4	3·8	0·34	1·05	39·8	31·9	7·2	15·1	9·6	27·4	15·1
C	8·3	5·0	0·35	0·77	38·5	26·5	7·2	12·1	7·2	32·7	16·3

• 3 samples. † 5 samples.

TABLE 2

Median Values of Analyses of Eight Solonetz-like Soils

Horizon	pH	Conductivity (mmhos/cm.)	Organic carbon	Inorganic carbon	Mechanical analyses						
					Total sand greater than 50 μ	Total silt 50–2 μ	Coarse silt 50–20 μ	Medium silt 20–5 μ	Fine silt 5–2 μ	Total clay less than 2 μ	Fine clay less than 0·125 μ
A_1	6·4	0·4	3·71	0·03	37·7	35·4	14·6	15·5	5·3	26·4	15·7
A_2•	5·7	0·4	2·24	T	38·7	34·8	16·5	13·1	5·2	25·0	15·9
B_1	6·5	0·3	1·31	T	30·8	27·4	11·5	12·0	3·9	36·2	24·1
B_2	7·9	0·5	0·73	1·95	38·9	29·6	11·3	13·7	4·7	29·9	16·4
B_3†	8·0	0·6	0·61	1·39	42·9	26·1	9·9	11·8	4·4	30·6	16·0
C	8·1	0·4	0·38	1·38	43·2	25·2	8·3	11·2	5·7	30·3	14·5

• 3 samples. † 6 samples.

with the lower B and C. The most strongly leached horizons (A_2 and A_3) have the lowest contents of fine silt.

3. For the clay fractions the highest values are found in the upper B horizon (B_1). This is true for both total clay (less than 2 μ) and for fine clay (less than 0·125 μ). The B_1 horizon contains about two and a half times as much total clay as the A_2, and about one-quarter more than the C horizon. For the fine clay fraction the B_1 horizon contains almost three times as much as the A_2, and about half as much again as the C horizon. This marked accumulation of clay is reflected in the very hard, clayey B horizons observed in the field.

4. The total sand (greater than 50 μ) content remains fairly constant in the solodized solonetz profile except in those profiles where an A_3 horizon occurs. This horizon contains more than 50 per cent. sand, considerably more than the percentages reported for other horizons. The A_3 horizon, as defined by Saskatchewan pedologists, is the most strongly leached portion of the A horizon, distinguishable from the A_2 horizon by its lighter colour and weaker structure.

5. The values for pH show all A horizons to be moderately acid. The A_2 and A_3 horizons are somewhat more acid than the A_1. The B_1 horizon is neutral in reaction while the lower B and C horizons are moderately alkaline. This alkalinity is largely due to the presence of calcium carbonate in the lower horizons. The values for conductivity are very low to low in the A and B_1 horizons. They increase with depth to moderately high values in the C horizon.

6. The organic-carbon content of the solodized solonetz soils decreases with depth as in most grassland soils (Mitchell *et al.*, 1944). However, a slight accumulation of organic carbon is shown in the B_1 horizon, notably in comparison with the A_3 horizon.

Median values of analytical results for eight solonetz-like soils are shown in Table 2. These results show:

1. Characteristics similar to the solodized solonetz soils with respect to the distribution of silt and clay. However, the relative increases in silt and decreases in clay content of the A horizons are less marked in the solonetz-like soils. Similarly, the accumulations of total clay and fine clay in the B_1 horizon are less marked in the solonetz-like soils. The pH values for the solonetz-like soils show the A horizons to be somewhat less acidic and the B_1 horizon more acidic than the corresponding horizons in the solodized solonetz soils. The pH values for the lower B and C horizons are somewhat less alkaline in the solonetz-like soils.

2. The conductivity of all horizons in the solonetz-like soils is very low in contrast to the increasing values found with increasing depth in the solodized solonetz soils.

3. A somewhat higher organic-carbon content is found in all horizons of the solonetz-like profiles as compared with the solodized solonetz.

4. The above differences, together with field, morphological, and laboratory studies (Janzen and Moss, 1956) support the suggestion that the solonetz-like soils are better drained but are less leached or degraded than the solodized solonetz soils.

Descriptions and analytical results for four individual profiles are listed in Tables 3 to 6. Profiles 1 and 2 represent solodized solonetz profiles from the Black and Grey Wooded Soil Zones, respectively. Profile 3 is a Brown solonetz-like soil, while Profile 4 is a Dark Brown regional prismatic soil included for comparison of a comparatively unleached soil with the strongly leached solonetzic soils.

Profile 1 (*Table 3*)

Black solodized solonetz profile developed on lacustrine clay. Sampled on gently undulating lacustrine plain. Well-drained surface and profile. Vegetation—grass. Longitude 54° 04′ W. Latitude 108° 24′ N. Elevation 1,660 ft.

A_1	0–3·5″[1]	Dark grey to black (10 YR 4/1–2/1). Columnar to coarse platy structure, crushing to granular. No calcium carbonate.
A_2	3·5–5·5″	Grey to dark grey (10 YR 5/1–4/1). Platy structure, crushing easily to fine granular. No calcium carbonate.
A_3	5·5–7″	Light grey (10 YR 7/2) weak platy structure, crushing easily to fine granular. (Not sampled.) No calcium carbonate.
B_1	7–15″	Dark grey (10 YR 4/1), round-topped columnar structure, plastic when wet, very hard when dry. Breaks to nutty (angular-fragmental) micro-structure. Particles have waxy coating of organic matter. No calcium carbonate.
B_2	15–19″	Olive-brown (2·5 Y 4/4). Columnar structure, breaks to irregular small clods, compact and moderately hard. No calcium carbonate.
B_3	19–32″	Greyish brown to grey (10 YR 5/2–5/1) weakly columnar, soft, compact. Moderate calcium carbonate content.
C	32–48″	Varved clay, colours light to dark grey (10 YR 7/1–4/1). Compact. Moderate calcium carbonate content.

Profile 1 represents a solodized solonetz soil from the most northerly island of Black (Chernozemic) soils in Saskatchewan. The profile is developed on glacial lacustrine deposits which are characterized by increasing clay content with depth as shown by the values for total clay in Table 3. From these values it would appear that no clay accumulation occurs in the B horizon. However, the values for fine clay indicate a small but significant increase of clay (over 5 per cent.) in the B_1 as compared with the C horizon.

The values for the silt fraction show an increase in total, coarse, and medium silt in the A horizons as compared with the B and C horizons. On the other hand the content of fine silt in the A horizons is lower than that of the lower B and the C horizons. The distribution of the silt and fine clay fractions in Profile 1 is, therefore, characteristic of solodized solonetz soils as shown in Table 1. However, in this profile the total sand content is less uniform, being highest in the A horizon and dropping to less than 1 per cent. in the lower B and C horizons. The coarse silt is likewise very low in these horizons.

Profile 2 (*Table 4*)

Grey podzolic-solonetzic profile developed on lacustrine clay. Lower B and C horizons heavier-textured than A and upper B horizons. Very

[1] Numbers refer to soil colours as outlined in Munsell Soil Color Charts. (1954.)

TABLE 3

Partial Analyses of Profile 1—Black Solodized Solonetz

Horizon	*Depth (in.)*	*pH*	*Conductivity (mmhos/cm.)*	*Organic carbon*	*Inorganic carbon*	*Total sand greater than 50 μ*	*Total silt 50–2 μ*	*Coarse silt 50–20 μ*	*Medium silt 20–5 μ*	*Fine silt 5–2 μ*	*Total clay less than 2 μ*	*Fine clay less than 0·125 μ*
A_1	0–3·5	5·4	0·4	..	0·04	10·8	50·9	13·5	25·3	12·1	38·3	15·0
A_{2-3}	3·5–7	5·3	0·5	..	0·02	18·0	57·3	18·7	25·7	12·9	24·7	7·6
B_1	7–15	6·8	1·7	..	0·01	4·7	41·6	9·5	20·2	11·9	53·7	31·0
B_2	15–19	7·8	3·7	..	0·08	1·8	36·0	1·8	19·6	14·6	62·1	33·4
B_3	19–32	8·1	4·0	..	1·17	0·3	37·1	2·8	17·1	17·2	62·7	29·5
C	32–48	8·4	1·2	..	1·08	0·6	38·1	2·3	19·1	16·7	61·4	27·3

TABLE 4

Partial Analyses of Profile 2—Grey (podzolic)—Solodized Solonetz

Horizon	*Depth (in.)*	*pH*	*Conductivity (mmhos/cm.)*	*Organic carbon*	*Inorganic carbon*	*Total sand greater than 50 μ*	*Total silt 50–2 μ*	*Coarse silt 50–20 μ*	*Medium silt 20–5 μ*	*Fine silt 5–2 μ*	*Total clay less than 2 μ*	*Fine clay less than 0·125 μ*
A_0	2–0	..	..	..	..	..	..	..	..	..	..	..
A_1	0–1	6·4	0·4	3·08	0·04	28·9	39·3	10·4	18·6	10·4	31·2	11·2
A_2	1–7	5·6	0·3	1·02	0·01	24·5	35·3	11·8	12·9	10·5	40·3	17·2
B_1	7–18	4·8	0·3	0·68	0·01	22·6	25·3	7·8	10·3	7·2	52·1	28·9
B_2	18–29	6·4	4·0	0·71	0·72	6·1	29·0	5·1	12·9	11·0	65·0	26·0
C_1	29–44	7·9	5·7	0·79	0·77	3·9	28·3	4·9	10·8	12·5	67·9	26·1

gently undulating lake plain, moderately good drainage. Vegetation—second growth aspen and shrubs. Longitude 104° W. Latitude 53° 05′ N. Elevation 1,300 ft.

A_0 2–0″	Chiefly well-decomposed organic matter. No calcium carbonate.
A_1 0–1″	Dark grey (10 YR 4/1). Weak platy structure. No calcium carbonate.
A_2 1–7″	Grey (10 YR 5/1). Small cloddy macro-structure, breaking easily to platy aggregates. No calcium carbonate.
B_1 7–18″	Dark grey brown (10 YR 4/2). Large blocky-columnar structure, breaking to hard, angular and small blocky aggregates. No calcium carbonate.
B_2 18–29″	Faintly banded dark grey (10 YR 4/1) and brownish. Massive structure, breaking to weak columnar, then small blocky aggregates. Moderate content of calcium carbonate.
C_1 29–44″	Varved clay, dark and light bands (10 YR 4/1–5/1). Massive structure. Moderate content of calcium carbonate. Gypsum and other salts present.

The analyses of Profile 2 show an increasing content of total clay from the A horizon downwards, a feature very common in fine-textured lacustrine deposits. There is, however, a slight accumulation of fine clay in the B_1 horizon, and the A horizons contain more total and coarse silt than the B or C horizons.

An examination of the above two profiles (1 and 2) shows that while the values for the various soil separates vary in detail between profiles, the relative values are all of the same order. This suggests that the same processes have been active in the development of these soils regardless of their zonal position.

Profile 3 (Table 5)

Solonetz-like profile on gently undulating ground moraine. Well drained. Vegetation—grass and scattered clumps of aspen. Longitude 103° 09′ W. Latitude 49° 00′ N. Elevation 1,900 ft.

A_1 0–5″	Dark greyish brown (10 YR 4/2). Cloddy-columnar structure, soft, friable. No calcium carbonate.
B_1 5–14″	Dark brown (10 YR 4/3). Weak columnar structure, breaking to small nutty (angular-fragmental) aggregates. No calcium carbonate.
B_2 14–22″	Pale brown (10 YR 6/3). Columnar structure, breaking to irregular small clods, then to granular. Moderate content of calcium carbonate.
B_3 22–28″	Very pale to pale brown (10 YR 7/3–6/3). Faintly columnar to massive. Less calcium carbonate than above.
C 28–39″	Greyish brown (10 YR 5/2). Massive, compact. Moderate content of calcium carbonate.

Mechanical analyses for the solonetz-like profile (Table 5) show a 50 per cent. increase in total silt in the A_1 horizon as compared with the B_1, and a 15 per cent. increase as compared with the lower B and C horizons. The coarse silt shows an increase of approximately 40 per cent. in the A_1 as compared with the B horizons, and a 66 per cent. increase over the C horizon. The fine silt decreases slightly in the B_1 horizon as compared with the A_1 horizon, then increases to a maximum in the C horizon.

TABLE 5

Partial Analyses of Profile 3—Brown Solonetz-like

Horizon	*Depth (in.)*	*pH*	*Conductivity (mmhos/cm.)*	*Organic carbon*	*Inorganic carbon*	*Total sand greater than 50 μ*	*Total silt 50–2 μ*	*Coarse silt 50–20 μ*	*Medium silt 20–5 μ*	*Fine silt 5–2 μ*	*Total clay less than 2 μ*	*Fine clay less than 0·125 μ*
A_1	0–5	6·2	0·4	3·12	0·01	45·7	30·8	11·5	15·0	4·3	23·5	12·5
B_1	5–14	6·0	0·4	1·10	T	43·8	20·8	8·1	9·6	3·2	35·4	22·8
B_2	14–22	8·0	0·4	0·70	1·95	42·5	26·6	8·7	13·5	4·4	31·0	14·7
B_3	22–28	8·4	0·8	0·39	1·39	42·1	27·7	9·9	12·7	5·1	30·3	13·3
C	28–39	8·1	4·1	0·35	1·05	43·2	26·5	6·9	12·8	6·8	30·3	13·8

TABLE 6

Partial Analyses of Profile 4—Dark Brown Prismatic

Horizon	*Depth (in.)*	*pH*	*Conductivity (mmhos/cm.)*	*Organic carbon*	*Inorganic carbon*	*Total sand greater than 50 μ*	*Total silt 50–2 μ*	*Coarse silt 50–20 μ*	*Medium silt 20–5 μ*	*Fine silt 5–2 μ*	*Total clay less than 2 μ*	*Fine clay less than 0·125 μ*
A_1	0–4	7·3	0·5	4·52	0·14	43·6	31·5	14·2	13·7	3·6	25·0	13·3
B_1	4–10	6·7	0·5	1·44	0·03	53·9	19·2	7·3	9·6	2·2	26·6	17·5
B_2	10–13	7·7	0·4	0·64	1·93	48·0	23·4	8·2	10·7	4·6	28·4	17·6
B_3	13–21	7·9	0·5	0·39	2·09	47·4	23·6	8·4	10·4	4·8	29·0	14·2
C_1	21–27	8·1	0·7	0·11	2·08	46·7	23·7	7·8	10·9	5·0	29·3	15·3

Total and fine clay show an increase in the B horizons as compared with the rest of the profile. The differences in total clay, however, are less marked than they are in the solodized solonetz profiles.

Profile 4 (*Table 6*)

Dark Brown regional prismatic profile on a gently rolling till plain. Vegetation—grass. Longitude 106° 30′ W. Latitude 51° 30′ N. Elevation 2,000 ft.

A_1	0–4″	Dark greyish brown (10 YR 4/2). Columnar structure, breaking to small cloddy. No calcium carbonate.
B_1	4–10″	Brown (10 YR 5/3). Columnar structure, breaking to small irregular clods, and fine granular. No calcium carbonate.
B_2	10–13″	Light brownish grey (10 YR 6/2). Weak columnar, breaking to fine granular. Soft. Moderate calcium carbonate content.
B_3	13–21″	Light grey (10 YR 7/2). Weak columnar to massive. Soft. Moderate calcium carbonate content.
C_1	21–27″	Light grey (10 YR 7/3). Massive, breaking to hard small cloddy, and coarse granular. Less calcium carbonate than above.

Analytical results for the dark brown prismatic-structured profile (Table 6) show a very low salt content throughout the profile in contrast to the increasing salt content shown for the lower B and C horizons of the solodized solonetz profiles. The dark brown soil is higher in inorganic carbon.

The mechanical analyses for the regional prismatic profile show twice the amount of coarse silt in the A horizon as compared with the B_1, and somewhat less than twice the amount found in the lower B and C horizons. The medium silt is approximately one-third greater in the A horizon than in the lower horizons. Total clay shows a gradual increase with depth, with the C horizon having the highest clay content. The fine clay, however, shows a very slight accumulation in the B_1 and B_2 horizons as compared with the A and C horizons.

These results suggest that this profile has undergone only slight leaching during the course of its development.

Discussion

Referring to the main objectives of this study, the data presented confirm the field evidence of clay accumulation (finer texture) in the upper B horizons of the solodized solonetz and solonetz-like soils investigated. The solodized solonetz soils show a greater accumulation of clay in the B_1 horizon than the solonetz-like soils, which agrees with the field evidence that the former soils have finer-textured upper B horizons. The textures and structures of the A and B horizons suggest they belong to leached or solodizing solonetz profiles. These features are less strongly expressed in the solonetz-like soils.

The morphology and composition of solodized solonetz soils representing the various major soil zones of Saskatchewan are reasonably similar. The chief differences in the soils are those of colour and organic-matter content of the A_1 horizons, which can be related to the climatic-

vegetational conditions of the respective zones. It would appear that the processes responsible for the development of solodized solonetz soils are otherwise independent of the zonal factors; and solodized solonetz profiles, wherever they occur in Saskatchewan, exhibit more similarities than differences in both morphology and physical composition.

The solonetz-like soils also occur in all major soil zones, but since most of them lack an A_2 horizon and a well-developed round-topped columnar B they do not present such a striking appearance as the solodized solonetz profiles. For this reason the solonetz-like soils are less likely to be considered apart from the soils regarded as zonal types. Nevertheless, the major features of the solonetz-like soils also appear to be independent of their zonal position.

Generalized descriptions of the solodized solonetz and solonetz-like soils are given in a previous paper (Janzen and Moss, 1956), together with data on exchangeable cations. This information, along with the present studies on mechanical composition, carbon, pH, and conductivity, serves to identify and characterize the two types of soil as they occur in Saskatchewan. The problem of understanding the genesis of these soils remains to be solved.

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CHEMICAL DISCRIMINATION OF TERRA ROSSAS AND RENDZINAS

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Summary

One of the discriminant functions of mathematical statistics is used in a re-examination of the chemical features of some terra rossas and rendzinas from South Australia. The results indicate that these soils constitute a bimodal group chemically. Dichotomy is therefore justifiable on chemical as well as on morphological grounds.

The use of a discriminant function in taxonomic work is illustrated by an application to some extra-Australian terra rossas and rendzinas. The result suggests that soils with similar morphological features usually have similar chemical features.

Introduction

In his study of their chemical features, Stace (1956) found that the average value of nearly every feature for terra rossas differed from the corresponding average for rendzinas. For any one feature, however, the range of values for terra rossas usually overlapped the greater part of that for rendzinas and consequently no single chemical feature could be used as a criterion for classification. Stace also found that the colour of any one of these soils was determined mainly by its contents of free ferric oxide and organic matter. The ratio of free ferric oxide (present as clay-sized particles) to nitrogen was, with few exceptions, greater than 10 for a terra rossa and less than 10 for a rendzina. The few exceptions would, of course, be misclassified if this ratio were used as the distinguishing feature.

Since Stace almost succeeded in separating terra rossas and rendzinas by means of a ratio of two chemical features, it seemed likely that success would be obtained by use of a discriminant function, a function of mathematical statistics designed for the solution of similar taxonomic problems. The discriminant function selected for this project was originally proposed by Fisher (1936) for allocating correctly an individual known to be a member of one of two taxonomic groups. It is a linear combination of numerical values for two or more features of the individual, its exact form being determined from the values of these features for typical members of each group. In the ideal case, such a function will yield two widely separated sets of values for members of the two taxonomic groups.

It was supposed in this instance that a soil, known to be either a terra rossa or a rendzina, had been submitted for classification by means of its chemical features. A discriminant function had therefore to be constructed from the chemical features of typical terra rossas and rendzinas (Stephens, 1956) and the samples used by Stace were selected for this purpose. The principal goal of this project, of course, was not the

classification of the hypothetical soil; it was to discover if terra rossas and rendzinas could be discriminated chemically.

It appears that pedologists have not made use of discriminant functions either in taxonomic work or in any other work that involves the allocation of a soil to one of two or more classes on the basis of two or more of its properties. There are several of these functions, each devised for the solution of a particular problem, and most of them should prove helpful in pedology. Any feature of a soil, chemical, physical, or morphological, to which a numerical value can be assigned, may be used in the construction of these functions.

The Discriminant Function

Assume that the discriminant function is to be constructed from three chemical features, the numerical values of which for any one terra rossa or rendzina are denoted by x_1, x_2, and x_3. Then the function, F, is given by

$$F = m_1x_1+m_2x_2+m_3x_3,$$

in which the coefficients m have to be determined. Suppose this has been done. One set of values for F can then be found for the typical terra rossas and another for the typical rendzinas. Each set has a range and a mean value. Now the coefficients are so determined that the most favourable compromise possible is secured between a large difference of the mean values and a small range in each set. In other words, they are chosen in such a way that the maximum separation of the two sets of values for F is obtained.

It can be shown that only the ratios of the coefficients to each other, not their actual values, are effective in securing the desired separation. The actual values may therefore be adjusted arbitrarily, provided that the ratios are not altered, and one of them is usually made unity because this simplifies the calculations of values for F.

The Chemical Features

Since the object of this work was to separate by means of chemical features soils that were separable by means of visible features, selection of the chemical properties was based mainly on their relation to these visible features. An overriding requirement, however, was the existence of a significant difference between the mean values of a feature for the two groups of soils; if the feature has the same mean value for both groups, it cannot provide information on differences between the groups.

The most obvious contrast between terra rossas and rendzinas is colour, and the contents of free ferric oxide and organic matter were therefore the first chemical features selected. The visible presence of calcium carbonate is also used in classifying these soils; the corresponding chemical feature is the content of calcium carbonate and a fairly closely related one is the reaction. The fifth and last selection was loss on ignition. This is admittedly an unsatisfactory quantity in many respects, but its correlations with other chemical features were different for the two groups of soils and this indicated that it might be of use in separating them.

Because features of a soil profile as a whole are used in its classification, each chemical feature was used in the form of its weighted mean value for the profile. Each weighted mean was calculated as follows. The analytical result for each sample from a profile was multiplied by the thickness of the horizon represented by the sample, and the sum of all these products was divided by the total thickness of the horizons. For example, the contents of organic carbon for one of the rendzinas were 4·5, 2·7, and 1·8 per cent. for sampled depths 0–2, 2–6, and 6–12 in., respectively. The weighted mean content was therefore

$$(4{\cdot}5\times2)+(2{\cdot}7\times4)+(1{\cdot}8\times6)\div(2+4+6) = 2{\cdot}6 \text{ per cent. approx.}$$

(The simple mean, given by $(4{\cdot}5+2{\cdot}7+1{\cdot}8)$ 3 which equals 3·0 per cent., is clearly not representative of the profile as a whole; the average content of five-sixths of the sampled depth is less than this mean.)

The weighted mean contents used as chemical features in this project are recorded in Table 1. They were derived from the analytical results

TABLE 1

Weighted Means used as Chemical Features

Soil	*Organic carbon* (%)	*Free* Fe_2O_3 (%)	$CaCO_3$ (%)	*pH*	*Loss on ignition* (%)
TR 1	2·6	6·0	0·46	8·0	9·8
2	2·2	4·6	0·02	7·7	9·6
3	1·8	4·1	0·01	7·2	6·4
4	2·7	4·0	0·11	8·3	10·9
5	2·4	7·8	0·02	7·0	10·0
6	0·5	1·1	0·24	8·6	2·5
7	1·7	2·9	0·22	8·2	5·2
8	2·3	4·3	0·01	6·4	9·1
9	1·7	5·8	0·04	7·2	8·7
10	1·2	2·8	0·01	7·1	5·2
R 1	3·5	2·1	2·9	8·3	9·3
2	2·9	3·7	1·6	8·3	9·6
3	2·9	1·0	12·3	8·4	13·9
4	4·0	2·8	2·2	8·6	11·4
5	3·1	2·9	0·9	8·5	9·0
6	2·6	0·15	1·6	8·2	9·4
7	6·0	1·4	0·6	7·8	14·9
8	4·9	2·8	0·14	7·2	12·2
9	2·4	0·8	0·05	7·7	11·6

given by Stace and Rogers (1954). Two differences between these features and those used by Stace (1956) should be noted. Since the chemical determination is less involved, total free ferric oxide was selected instead of that portion present in the soil as clay-sized particles. Organic carbon was preferred to nitrogen as a measure of organic matter because its weighted means had more suitable statistical properties.

Chemical Separation of the Two Groups

The efficacy of a discriminant function in separating two groups of soils is not necessarily increased if more features are used in its construction. An added feature may not provide further information on differences between the groups because it is closely correlated with one already included. It was mainly for this reason that five of these functions were constructed. Another reason why several functions may prove useful becomes apparent in the next section.

Use of the contents of organic carbon and free ferric oxide yielded the function.

$$F_1 = (\text{org. C})\% - 0{\cdot}558\ (\text{free } Fe_2O_3)\%.$$

That is, the value of F_1 for a terra rossa or a rendzina is obtained by subtracting 0·558 of the percentage content of free ferric oxide from that of organic carbon. The values for the ten terra rossas were, in order of magnitude,

−1·95, −1·54, −0·75, −0·49, −0·37, −0·36, −0·11, −0·10, 0·08, 0·47;

and those for the nine rendzinas were

0·84, 1·48, 1·95, 2·33, 2·34, 2·44, 2·52, 3·34, 5·22.

Since the highest value for a terra rossa, 0·47, was less than the lowest for a rendzina, 0·84, the discriminant function F_1 enabled a chemical separation of the two groups.

The tendency of each set of values to form a cluster is more apparent in a diagram and they are therefore given again in Fig. 1. A tentative conclusion is that terra rossas and rendzinas constitute a bimodal group of soils chemically and dichotomy is justifiable. The use of contents of organic carbon and free ferric oxide by a chemist may be regarded as equivalent to the use of colour by a pedologist.

The other discriminant functions constructed were:

$$F_2 = (\text{org. C})\% - 0{\cdot}501\ (\text{free } Fe_2O_3)\% + 0{\cdot}147\ (CaCO_3)\%;$$
$$F_3 = (\text{org. C})\% - 0{\cdot}472\ (\text{free } Fe_2O_3)\% + 0{\cdot}567\ (\text{pH});$$
$$F_4 = (\text{org. C})\% - 0{\cdot}444\ (\text{free } Fe_2O_3)\% + 0{\cdot}436\ (\text{pH}) + 0{\cdot}123\ (CaCO_3)\%;$$
$$F_5 = (\text{org. C})\% - 0{\cdot}617\ (\text{free } Fe_2O_3)\% + 0{\cdot}673\ (\text{pH}) + 0{\cdot}094\ (CaCO_3)\% + 0{\cdot}164\ (\text{loss on ign.})\%.$$

The values of each function for the individual soils are recorded as dot diagrams in Fig. 1.

Inspection of the figure reveals that each function enables the chemical separation of the two groups of soils and that each set of values, particularly those for the terra rossas, clearly tends to form a cluster at or near its mean value. This confirms the tentative conclusion that terra rossas and rendzinas constitute a bimodal group of soils chemically and dichotomy is justifiable.

Two points observable in Fig. 1 are of interest. One of the terra rossas represented by the cluster of dots near the mean and the rendzina

represented by the dot on the extreme left, in each diagram, were taken from sites separated only by a roadway. Pedologists are in no doubt about the classification of either of these soils. Since, however, the vertical broken lines in the figure denote the (statistically determined)

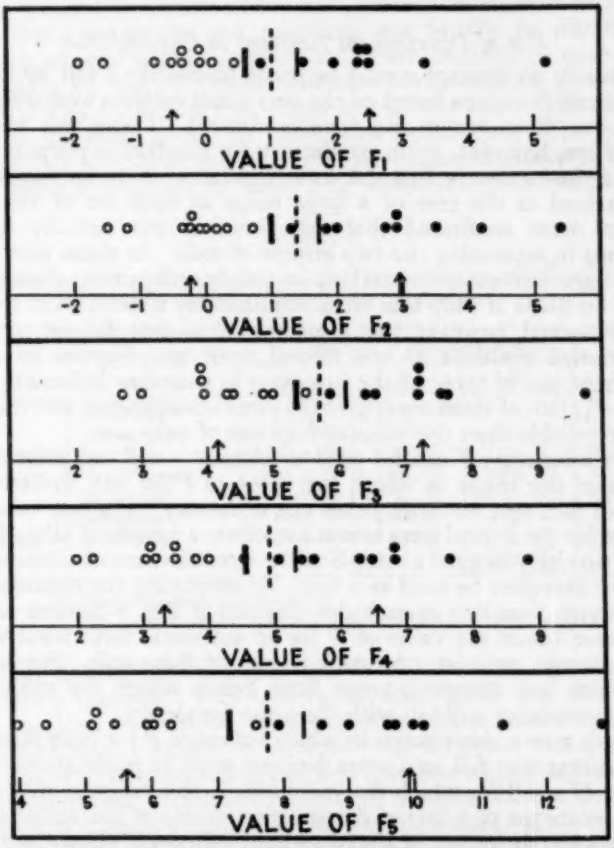

FIG. 1. Dot diagrams of values of discriminant functions. (Open dot—terra rossa: full dot—rendzina. Arrow heads indicate mean values. Other symbols, see text.)

chemical demarcation between the groups, a chemist would classify the rendzina as an outlying terra rossa if he used function F_1 or F_2. This suggests that there has been a greater change in morphology than in chemical features over the short distance between the two sites.

The second point of interest is that the dots representing terra rossas and rendzinas from the south-east of South Australia are randomly scattered among the dots representing soils from the area around Adelaide. (Table 1, in which both the terra rossas and the rendzinas from the south-east are nos. 6–9, shows that this is usually true also for

individual chemical features.) This means that the soils of each group, although formed from very different parent materials (Norrish and Rogers, 1956) and under somewhat different climatic conditions (Stace, 1956), are as alike chemically as they are morphologically.

Use of Discriminant functions in Classification

Ordinarily no attempt would be made to classify a soil by means of discriminant functions based on the very small samples available for this project (ten terra rossas and nine rendzinas). Those that were constructed are, however, quite satisfactory for illustrative purposes.

Fig. 1 shows clearly that the wide separation of mean values for F_5 was obtained at the cost of a large range in each set of values, and statistical tests confirmed that this function was actually the least efficacious in separating the two groups of soils. As these tests did not differentiate the other functions, a purely subjective choice would usually be made if only one were required for classification purposes. It was observed, however, that most individual dots did not occupy the same relative positions as one moved from one diagram to another. Concurrent use of three of the functions is therefore indicated, say F_2, F_3, and F_4; two of them must give the same classification and this would be more reliable than that obtained by use of only one.

Before a function F can be used to classify a soil, an estimate must be made of the range in which the value of F for any authentic terra rossa will fall, say, nineteen times out of twenty. The ten values of F obtained for the typical terra rossas constitute a sample of all such values and are precisely as good a sample as the ten soils were of all terra rossas. They can therefore be used as a basis for estimating the required range.

The short, thin line in each dot diagram of Fig. 1 denotes an upper limit above which the value of F for an authentic terra rossa will fall, on the average, only once for each twenty of these soils. Similarly, the short, thick line denotes a lower limit below which the value for an authentic rendzina will fall with the same frequency.

There is now a short range in which values of F for both terra rossas and rendzinas may fall, and some decision must be made about the classification of a soil for which the value falls in this range of doubt. This is done by means of a line of demarcation drawn at the statistical midpoint between the means of the two sets of values and shown as a broken line in each dot diagram. If a value for F falls to the right of this line, the soil is classified as a rendzina; if it falls to the left, the classification is terra rossa. The decision for a value that fell in the range of doubt would, of course, be suitably qualified.

The existence of such a range by no means renders a discriminant function valueless as an aid in taxonomic problems. This is because a system of classification based on a function constructed from a few chemical features would certainly not be an exact parallel of a morphological system. A soil that was difficult to classify by the latter—that is, a soil that fell in a morphological range of doubt—would probably not be difficult to classify by the former. The converse is illustrated by the

morphologically typical rendzina, mentioned in the preceding section, for which each of the five values for F falls in the range of doubt.

Application to Some Extra-Australian Soils

In an attempt to secure additional evidence in support of the conclusion that terra rossas and rendzinas can usually be discriminated chemically, several extra-Australian soils were classified by means of the functions F_2, F_3, and F_4. These soils have been classified as terra rossas or rendzinas in the country of origin and all but one would have been placed in the same group by Australian pedologists. The necessary chemical data were supplied by Stace (private communication).

The result is recorded in Table 2 in which are given the country of

TABLE 2

Classification of Extra-Australian Terra Rossas and Rendzinas by use of Discriminant Functions

Coutry of origin	*Original classification*	*Values of F and classifications*			*Decision**
		F_2	F_3	F_4	
France	Rendzina	5·33, R	5·64, T?	8·36, R	Rendzina
France	Terra rossa	−0·52, T	3·86, T	3·31, T	Terra rossa
South Africa	Rendzina	4·10, R	7·29, R	7·56, R	Rendzina
South Africa	Terra rossa	0·01, T	4·70, T	3·68, T	Terra rossa
Canada	Rendzina	7·49, R	11·7, R	11·0, R	Rendzina
Trinidad	Rendzina	0·67, T	4·92, T	4·07, T	Terra rossa
New Zealand	Rendzina	7·94, R	6·59, R	10·6, R	Rendzina
New Zealand	Brown rendzina	0·59, T	4·37, T	3·59, T	Terra rossa

* Based on chemical features.
? Indicates that the value of F fell in the doubtful range.

origin, the original classification, the values of F_2, F_3, and F_4, and the classification associated with each value, and, finally, the decision that would be given in practice. The brown rendzina from New Zealand would have been classified as a terra rossa by Australian pedologists (Stephens, private communication) and therefore all but one of the eight soils were classified correctly by means of the discriminant functions.

This result is good evidence for the general validity of the conclusion that terra rossas and rendzinas (as defined by Stephens, 1956) can usually be discriminated chemically. It has the obvious implication that soils which are similar morphologically are usually alike chemically, whatever the country of origin, since the discriminant functions were constructed from chemical features of soils from only one country.

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RELATION BETWEEN TRACE-ELEMENT CONCENTRATIONS IN SOIL AND PARENT MATERIAL

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Summary

An examination of nineteen soil profiles from Queensland and eighteen from Central Australia, both lots formed from a variety of parent materials, and of seventeen profiles formed from dolerite in Tasmania, has shown that the relation between the concentration of a trace element in a soil and its concentration in the parent material is often not close enough for satisfactory estimation of the former from the latter. This is because pedogenic factors other than parent material also play important parts in determining the concentration in the solum. During the weathering processes the range of concentration of a trace element may be greatly increased, and at a later stage the range may be reduced almost to its original value. Although the increase may be quite general, the reduction in range appears to occur mainly within taxonomic groups. Thus no more than a rough indication of the average concentration of a trace element in a solum can usually be obtained from its concentration in the original parent rock. There may, however, be a fairly close relation between the concentrations in the solum and the C horizon (weathered parent material) of a profile, particularly when effects produced by disturbing factors within taxonomic groups are excluded.

Introduction

THE existence of a close relation between the concentrations of a trace element in a soil and its parent material would obviously be of value in agricultural research. The parent materials of large areas of Australian soils are known and the trace-element contents of these materials could be ascertained with much less work than would be required for analyses of the soils themselves. The close relation could then be used to estimate, from relatively few analyses of a parent material and with ample accuracy for agricultural purposes, the trace-element status of the large areas of soil developed from this material.

In his account of trace elements generally, Mitchell states that the trace-element content of a soil is dependent almost entirely on that of the rocks from which the soil parent material was derived and on the weathering processes to which the soil-forming materials have been subjected (Bear, 1955, p. 254). He then discusses the distribution of trace elements in rocks and concludes (loc. cit., p. 261) that a knowledge of this distribution 'enables one to anticipate with some degree of accuracy the approximate total content of some constituents to be expected in any particular soil'. Unless this and similar statements mean only that the content can be estimated very roughly—for example, as low, medium, or high—they imply the existence of a close relation between the trace-element contents of soil and parent material. It appears, however, that no quantitative determination of this relation has been made.

The determination reported here was made with analytical results for three lots of samples. One lot consisted of nineteen profile samples from Queensland, each of which included a sample of the C horizon. These profiles had been used in a survey of the trace-element status of Queensland soils (Oertel and Giles, 1958); they included members of eight taxonomic groups and were formed from widely differing parent materials. The second lot consisted of seventeen profile samples from Tasmania, each of which included a sample of fresh parent rock and most of which included one or more samples of weathered rock (C horizon). These profiles had been used in a geochemical study of soil development (Tiller, 1958); they included members of four taxonomic groups and all were formed from dolerite. The third lot consisted of eighteen profile samples from Central Australia, each of which included a sample of the C horizon. These samples had been used in a survey of the trace-element status of soils in Central Australia (McKenzie, in preparation for publication); they included members of taxonomic groups with widely different properties.

Analytical Results

Cobalt, copper, manganese, molybdenum, and zinc were determined for the Queensland and Central Australian profiles, the first four by an optical spectrographic method and the last by fluorescent X-ray spectroscopy. The first four elements plus nickel and zirconium were determined for the Tasmanian profiles by the same optical spectrographic method. The methods used are known to give results with a standard error of about 10 per cent., except where the concentrations are very low. All concentrations were expressed as parts per million of the mineral matter of the sample.

A weighted mean concentration of each element was calculated for the solum of each profile by weighting the result for each sampled horizon according to the thickness of the horizon. This weighted mean is a measure of the average concentration in the A and B horizons or their equivalent, and it is immaterial (for these soils) whether this concentration is taken as a fraction of the total fine earth sample or of the mineral matter of this sample. The weighted mean concentrations and the concentrations in the C horizons for the Queensland profiles are recorded in Table 1; this table also gives the classification (Stephens, 1956) and the parent material of each profile. The weighted means and the concentrations in the fresh parent rock (not the C horizon) for the Tasmanian profiles appear in Table 2, where the classification of each profile is also given. No geological information was available on the parent materials of the Central Australian profiles. In addition, there was only one profile each for all but two of the represented taxonomic groups and several profiles could not be classified satisfactorily. For these reasons the original chemical data for this lot of profiles are not included here.

Examination of Data

The data in Tables 1 and 2 were studied separately and three aspects of the relation between trace-element contents of soils and parent

TABLE 1

Concentrations in Solum and C Horizon

(Upper member of pair: Solum; lower member: C horizon)

Classification	*Parent material*	Co *p.p.m.*	Cu *p.p.m.*	Mn *p.p.m.*	Mo *p.p.m.*	Zn *p.p.m.*
Grey and Brown Soils of Heavy Texture	Calcareous sandstone	15·5	49	1,670	8·0	60
		7·9	46	850	9·1	90
	Clay sediments	12·9	41	550	6·6	99
		7·9	43	190	7·6	46
	Sediments	11·8	41	960	7·6	66
		8·9	49	740	7·9	100
Black Earths	Diorite	72	33	2,570	7·3	50
		36	16	850	8·3	41
	Basalt	67	92	1,700	9·7	93
		16	45	1,200	9·3	65
	Basalt	54	87	1,250	9·8	115
		35	70	790	8·8	98
	Basaltic alluvium	41	56	1,380	9·0	110
		33	51	1,200	10	140
	Clay alluvium	41	53	1,620	7·7	81
		36	46	1,600	7·8	90
Krasnozems	Basalt	66	83	1,630	15	103
		43	68	1,200	10	93
	Granodiorite	3·0	5·4	194	7·4	48
		5·0	6·2	430	6·7	48
	Basalt	28	93	770	19	104
		47	140	790	21	110
Rendzina	Limestone	6·8	44	335	5·8	71
		2·7	23	190	7·4	40
Red Brown Earths	Basic igneous rocks	20	46	850	8·8	60
		34	53	1,100	13	60
	Mixed alluvium	18	43	730	9·3	80
		25	48	1,100	9·6	99
	Granitic rocks	34	67	1,050	12	62
		30	54	980	8·5	57
Solodized Solonetz	Granitic rocks	4·5	10	160	4·8	22
		10	10	480	6·3	38
	Alluvium	6·3	21	130	5·2	37
		10	25	370	7·2	44
	Alluvium	15	40	990	7·6	52
		17	34	970	5·3	67
Red Podzolic	Sandstones	7·1	14	160	5·6	22
		1	4·5	43	4·8	18

material were examined. One of these aspects is the relation that obtains when each taxonomic group of soils is treated as a unit; is there a close relation between the average concentration of an element in a group of soils and its average concentration in the parent materials of the group? Another aspect is the relation within soil groups; is the weighted mean concentration of an element closely related to its concentration in the

parent material when differences between taxonomic groups have been eliminated? The third aspect is the general relation between the weighted mean concentration of an element in any soil and its concentration in the parent material of the soil. Given the concentration of a trace element in any parent material, how accurately can its average concentration in any soil derived from this material be estimated?

TABLE 2

Concentrations in Solum and Fresh Dolerite

(Upper member of pair: Solum; lower member: Dolerite)

Classification	Co *p.p.m.*	Cu *p.p.m.*	Mn *p.p.m.*	Mo *p.p.m.*	Ni *p.p.m.*	Zr *p.p.m.*
Krasnozems	55	180	1,700	14	72	390
	44	110	1,400	8·8	52	150
	27	150	660	12	150	340
	44	62	1,300	8·1	110	99
	69	130	960	16	155	220
	58	60	1,650	8·4	140	91
	67	170	1,120	13	155	220
	42	75	1,300	7·9	86	110
Black Earths	6·6	73	720	7·3	5	340
	28	110	1,200	8·3	8·3	200
	75	49	2,200	8·9	95	220
	58	58	1,350	7·6	140	87
	34	58	1,130	7·4	64	200
	30	65	1,160	7·9	67	94
	42	90	1,370	8·9	42	220
	32	97	1,400	7·6	44	140
Brown Earths	28	95	980	8·5	48	300
	47	99	1,150	8·5	63	170
	50	130	2,650	11	66	190
	46	110	1,350	7·9	65	140
	29	180	590	10	33	160
	48	110	1,350	8·3	58	160
	46	140	1,230	11	75	160
	48	89	1,400	9·3	69	140
Grey-Brown Podzolic Soils	36	81	810	9·4	45	280
	48	100	1,350	8·6	79	150
	25	120	640	7·9	13	220
	34	140	1,100	7·6	23	180
	41	110	590	8·3	56	170
	37	80	1,200	8·1	66	130
	24	115	720	7·7	12	250
	46	140	1,300	8·0	26	200
	34	73	750	9·9	31	450
	37	80	1,250	7·9	58	140

This examination was restricted to a search for only those relations that can be represented satisfactorily by the linear equation

$$y = a + bx$$

where y denotes the weighted mean concentration of the trace element,

x its concentration in the parent material, and a and b are constants. The ordinary correlation coefficient is a measure of the closeness with which the relation between two varying quantities approaches such a linear functional relation, and these coefficients were therefore determined for each aspect of the relation between weighted mean concentration and concentration in the parent material. The results for the Queensland profiles are recorded in Table 3 and those for the Tasmanian profiles in Table 5.

Discussion

(*a*) *The Soils from Queensland*

It is the third aspect of the relation between the two concentrations—the relation obtaining when each soil is treated as an independent entity—that is of most interest and Table 3 shows that there is a significant

TABLE 3

Correlation of Weighted Mean with Concentration in C Horizon for Queensland Profiles

Aspect of relation	Co	Cu	Mn	Mo	Zn
Groups as units . .	0·81•	0·78•	0·78•	0·88 •	0·89•
Within groups . .	0·47	0·83•	0·54	0·80 •	0·57
Over all samples . .	0·69•	0·81•	0·69•	0·83 •	0·72•

• Statistically significant at a probability level of 0·05 or less.

relation for each element between the concentration in the solum (the weighted mean) and that in the C horizon. In no case, however, can the relation be represented accurately by a linear equation and, as shown presently, an accurate estimate of the concentration in the solum could not be obtained from the concentration in the C horizon on this basis.

The standard error of such an estimate—a measure of the deviation of the estimate from the actual value—is given by $\sqrt{(1-r^2)}$ times the standard deviation of the sample of concentrations in the solum used to obtain the relation (r denotes the correlation coefficient). These standard deviations of the solum concentrations, for the three lots of profile samples, are given in Table 4. The standard errors of estimates for the

TABLE 4

Standard Deviations of Observed Concentrations in Solum (in p.p.m.)

Sample	Co	Cu	Mn	Mo	Ni	Zn	Zr
Queensland profiles . .	23	27	670	3·4	..	28	..
Tasmanian profiles . .	18	41	590	2·5	48	..	84
Central Australian profiles .	4·6	9·4	190	1·0	..	18	..

Queensland profiles, calculated from the values in Tables 3 and 4, are, in parts per million: Co 17; Cu 16; Mn 480; Mo 2; and Zn 20. These

errors, except that for manganese, may not appear excessive but they are more serious than their actual values suggest. In round numbers, the error of one estimate in three, on the average, will exceed the standard error and, when the standard errors are compared with the observed weighted means (Table 1), it is clear that an estimate of the weighted mean from the concentration in the C horizon can be no more than a rough indication—such as high, medium, or low—of this value for all elements except molybdenum.

The relation between concentrations in the solum and the C horizon when taxonomic groups are treated as units and that obtaining within the groups themselves are of interest because they provide information on the influence of pedogenic factors other than parent material. The 'group' correlation coefficients in Table 3 show that the average concentration in the solum for a taxonomic group is fairly closely related to the average concentration in the C horizons. On the other hand, only two of the 'within group' coefficients are significant, those for copper and molybdenum. Any relation, linear or non-linear, that is likely to exist between the trace-element contents of soil and parent material could be represented at least roughly by a linear equation and, if close, would have associated with it a correlation coefficient large enough to be statistically significant even for small samples. It can be concluded, therefore, that there is no evidence for any close relation between the contents of soil and parent material for cobalt, manganese, and zinc when the 'group' relation has been eliminated.

This result obviously suggests that pedogenic factors other than parent material have a strong influence in determining the trace-element content of a soil, but it gives no information either on the factors involved or on their effects. Some information on the latter can be obtained by a more detailed examination of the original data (Table 1).

There is a range of concentrations in the C horizon in each taxonomic group, and a necessary consequence is that the group averages will have different values. It was found, for each element, that the differences between the group averages were no greater than could be attributed to the variations within groups; that is, there were no real differences between the group averages for concentrations in the C horizons. This was not so, however, for the average concentrations in the solum; these group averages, as a whole, differed by more than could reasonably be attributed to the corresponding variations within groups. One explanation is that the other pedogenic factors have reduced the variation of the weighted means within taxonomic groups (making it smaller than the variation of concentrations in the C horizon) but not the variation between groups, and this explanation is accordant with the data for copper, molybdenum, and zinc. For cobalt, however, the variation within groups was not reduced but that between groups was increased, while both variations were slightly increased for manganese.

It can be concluded, therefore, that pedogenic factors other than parent material have a measurable influence on the concentrations of trace elements. Their effects are not the same for all elements but they have the common result that the concentration of an element in the

solum is only partly determined by its concentration in the weathered parent material (the C horizon). More information on these effects is provided by the Tasmanian profiles.

(*b*) *The Soils from Tasmania*

The samples used in the work on the Tasmanian profiles differed in one important respect from those of the Queensland profiles. The latter included parent materials, such as clay alluvium and sandstone, that had been through at least one previous weathering cycle and would therefore have attained some degree of chemical stability. The Tasmanian samples included parent material in the form of an unweathered igneous rock, dolerite, as well as in the form of weathered material. The fresh rock alone was used in the study of the relation between concentrations in soil and parent material because the samples of weathered dolerite covered such a wide range of degrees of weathering that they were not suitable for this study (although they provide useful information on the fate of trace elements in the transition from rock to soil).

Because parent material in the form of fresh rock differs much more from the final soil than does the weathered material of a C horizon, it is not surprising, in view of the results obtained from the Queensland profiles, that most of the correlation coefficients for the Tasmanian samples (Table 5) have low values. Only two of the coefficients for the

TABLE 5

Correlation of Weighted Mean with Concentration in Dolerite for Tasmanian Profiles

Aspect of relation	Co	Cu	Mn	Mo	Ni	Zr
Groups as units . .	0·54	−0·16	0·36	0·64	0·99*	−0·45
Within groups . .	0·63*	0·57*	0·27	0·20	0·86*	0·37
Over all samples . .	0·60*	0·18	0·29	0·39	0·82*	0·18

* Statistically significant at a probability level of 0·05 or less.

relation obtaining when each soil is treated as an independent entity are statistically significant. When these values for cobalt and nickel, together with the standard deviations for these elements (Table 4, Tasmanian profiles), are considered in the light of the discussion on standard errors of estimates, it is clear that no more than a rough indication of the concentration in a solum could be obtained from that in the fresh parent material. For the other elements—copper, manganese, molybdenum, and zirconium—a value picked at random from the observed weighted means (Table 2) would be as reliable as an estimate based on the concentration in fresh dolerite. This is so particularly for manganese and molybdenum because, as appears in the sequel (Table 6), the concentrations of these elements were probably almost constant for all samples of fresh dolerite, the observed variation in the analytical results being attributable to analytical error. It follows that the same estimate of the average concentration in the solum would be made for all seventeen profiles formed from this rock, although the observed values ranged from

590 to 2,650 p.p.m. for manganese and from 7·3 to 16 p.p.m. for molybdenum.

Taken as a whole, the results in Table 5 show that pedogenic factors other than parent material have had a marked effect on the concentrations in the solum of all elements except nickel because these concentrations depend only slightly, if at all, on the corresponding concentrations in fresh dolerite, whichever aspect of the relation between them is considered. The original data (Table 2) were therefore examined in more detail.

TABLE 6

Coefficients of Variation of Concentrations in Soil and Parent Material

	All concentrations as one sample			*Within taxonomic groups only*		
Trace element	*Fresh Dolerite*	*Weathered Dolerite*	*Solum*	*Fresh Dolerite*	*Weathered Dolerite*	*Solum*
Cobalt	20%	42%	45%	20%	38%	44%
Copper	27	55	36	26	48	21
Manganese	10*	60	53	9*	61	52
Molybdenum	5·6*	26	24	5·2*	13	12
Nickel	53	50	74	52	52	46
Zirconium	25	35	33	24	28	34

* All this variation may be due to analytical error and the actual concentration may have been practically constant.

For each element, the differences between the group averages of concentrations in fresh dolerite were no larger than could be attributed to variations in these concentrations within groups; that is, there were no real differences in the bodies of fresh dolerite that formed the parent material of the soils of the different taxonomic groups. However, the differences between the group averages of concentrations in the solum for copper, molybdenum, and nickel were much greater than could be attributed to variations within groups; that is, there were real differences between the taxonomic groups in the concentrations of these elements in the solum.

The explanation of this result is facilitated by use of the values in Table 6, which are also of interest in themselves. This table gives the coefficients of variation of the observed concentrations in fresh dolerite, weathered dolerite, and the solum. There are two sets of these coefficients; the values in the first set are measures of the dispersion of concentrations when all concentrations for an element are taken as one sample, while the values in the other set are measures of the average dispersion of concentrations within soil groups, all differences between groups being eliminated. Corresponding coefficients in the two sets have practically the same value when there are no real differences between taxonomic groups; this is illustrated by the values for fresh dolerite. (It should be noted that the value of a coefficient of variation is unaffected if, for example, all concentrations are doubled or halved.)

The first set of coefficients in Table 6 shows that an initial effect of the pedogenic processes was an increase in dispersion of all concentrations, except those of nickel, because the coefficients of variation become greater in passing from fresh to weathered dolerite. The increase in dispersion of the concentrations of nickel occurred in the transition from weathered dolerite to soil. A comparison of the two sets of coefficients for the solum shows that another effect of the pedogenic processes was a reduction in dispersion of the concentrations of copper, molybdenum, and nickel within the taxonomic groups. This reduction in dispersion within groups for molybdenum is already apparent in the weathered dolerite. The values for weathered dolerite and the solum in the first set of coefficients in Table 6 show that the reduction in dispersion within groups was not accompanied by any marked reduction in the overall dispersion.

One consequence of these changes in dispersion is that there are significant differences between the group averages of concentrations in the solum for some elements although the original parent rock may be considered to be uniform. Another consequence is that there is no close relation, on the whole, between the concentration of a trace element in the solum and its concentration in the parent rock.

The conclusion that can be drawn from these results is clearly similar to that obtained from the results for the soils from Queensland. In particular, it seems that the pedogenic factors producing a certain group of soils also act to reduce the range of concentrations of some elements from its value in the weathered materials (C horizons) of the group.

(*c*) *The Soils from Central Australia*

The data for the soils from Central Australia were not suitable for the detailed analysis to which the data for the other soils was submitted. They could, however, be used to study the most important aspect of the relation between the concentration in the solum and that in the C horizon, that is, the relation obtaining when each soil is treated as an independent entity. Although the soils were treated as units, the correlations coefficient for these profiles should be compared with the 'groups as units' values for the Queensland profiles. This is because most of the Central Australian profiles were single representatives of taxonomic groups and could therefore be considered as a sample of groups, not of individual soils. (Evidence already presented has indicated the importance of the taxonomic group in the relation between concentrations in the solum and the C horizon.)

The coefficients of correlation between concentrations in the solum and concentrations in the C horizon for the soils from Central Australia are given in Table 7. These values are, as a whole, higher than those obtained for the Queensland soils; they are high enough for estimates of the concentration in the solum to be made from that in the C horizon with sufficient accuracy for agricultural purposes. The errors of estimation, expressed as percentages, are included in Table 7. The error for molybdenum is particularly low, being comparable in magnitude with the analytical error.

TABLE 7

Correlation of Weighted Mean with Concentration in C Horizon for Central Australian Profiles and Error of Estimation of Former from Latter

Measure	Co	Cu	Mn	Mo	Zn
Correlation coefficient* .	0·94	0·93	0·90	0·80	0·87
Error of estimation . .	19%	18%	21%	12%	20%

* All values are statistically significant at the probability level 0·001.

Although these results are superficially promising, they are of no practical value, because it would be necessary to analyse a sample of the C horizon of each profile in order to obtain an estimate of a concentration in the solum and, as one sample per profile must be analysed, an analysis of a surface sample would be more generally useful. The only results of practical value would be correlation coefficients not lower in value than those of Table 7, but obtained for a variety of soils formed from essentially uniform parent material, such as the sample of soils from Tasmania.

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COMPOSITION OF THE SOLUBLE AND EXCHANGEABLE IONS OF THE SALTY SOILS OF THE MIRROOL IRRIGATION AREA (NEW SOUTH WALES)

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Summary

Salty soils of the Mirrool Area were found to be formed mainly by salt accumulation from lower soil layers. Under these conditions saline soils, or saline–alkali soils containing gypsum, were generally formed. The exception was one profile in which precipitation of carbonates had resulted in the formation of a saline–alkali soil not containing gypsum.

The soluble Na^+ percentage increased and the soluble Ca^{++} percentage decreased with depth in all but one profile. A high variability of these percentages in the A and B_1 horizons was attributed to precipitation of divalent ions, and application of fertilizers.

Some saline soils were base unsaturated. These soils had a high soluble Na^+ percentage, but had absorbed only small amounts of Na^+. Laboratory tests showed that permeability was reduced more in base unsaturated than in base saturated soils when exchangeable Na^+ was 10 per cent. or higher. The relevance of these findings to the classification of salty soils is briefly discussed.

Introduction

THE composition of the exchangeable cations and of the soluble ions is of importance for the correct management and reclamation of salty soils. It is well known that salty soils with a high exchangeable Na^+ percentage, but which do not contain gypsum, develop undesirable physical characteristics after removal of excess salt (Kelley, 1951; Richards *et al.*, 1954).

In many irrigation areas the formation of salty soils is mainly due to the accumulation of soluble salts derived from the irrigation water (Russell, 1950). A large number of irrigated soils are, furthermore, calcareous and often contain gypsum (Richards *et al.*, 1954).

In this paper a study is reported on the soils of the Mirrool Irrigation Area, which are irrigated with water of a very high quality. These soils did not contain gypsum before irrigation was introduced, and their A and B_1 horizons are usually non-calcareous (Taylor and Hooper, 1938). Some of the soils are even distinctly base unsaturated. It is thus of particular interest to compare the characteristics of the salty soils in this area with those of salty soils elsewhere, formed under different conditions.

General description of area

The Mirrool Irrigation Area is part of the Murrumbidgee Irrigation Areas, one of the principal irrigation areas of Australia. The climate is semi-arid, with an average rainfall of 15·5 in. Twenty thousand acres are used for horticulture, while 130,000 are under a rotation of pastures

and cereal crops which often include rice. The Mirrool Area was chosen for this investigation because its soils are representative of a large part of the existing irrigation areas. Similar soil types also occur in adjoining areas, of which 1,000,000 acres are to be supplied with irrigation water in the near future.

The soils of the Mirrool Area, described by Taylor and Hooper (1938), occur in a complex pattern on layers of different geological origin. A description of the soil physical characteristics and of the factors associated with salt accumulation has been given in other papers (Groenewegen, 1957, 1959).

The irrigation water contains 80 p.p.m. of soluble salts. Its high quality is shown by comparison with other river waters: White Nile 174 p.p.m.; Indus 300 p.p.m.; Colorado 795 p.p.m.; and Pecos 6,200 p.p.m. (Russell, 1950). The composition of the Murrumbidgee irrigation water in m.e./l. is as follows: Ca^{++} 0·45, Mg^{++} 0·45, Na^{+} 0·3, Cl^{-} 0·28, SO_4^{--} 0·25, and HCO_3^{-} 0·65 (Cassidy, 1949).

Methods

The different layers or horizons of twenty-three salty profiles, of the principal soil types of the area, were sampled. There were three to four samples of each profile, and the profiles were samples to a depth of 3–4 ft. In some cases groundwater samples were also taken.

Saturated pastes were prepared of all the soil samples, and the soluble ions in the saturation extracts were determined (Richards *et al.*, 1954).

Exchangeable cations were determined on eleven profiles and the exchangeable Na^{+} percentage on another four profiles. Exchangeable cations were extracted with N NH_4Cl, pH 7 (Piper, 1942), and in the case of calcareous samples with N NH_4Cl, in 60 per cent. ethanol pH 8·5 (Tucker, 1954). Since gypsum was present in some samples SO_4^{--} was determined in the NH_4Cl extracts, and these values were subtracted from the Ca^{++} obtained in these extracts. The corrected values were reported as exchangeable Ca^{++} (Piper, 1942).

Analytical methods were: Cl^{-}, SO_4^{--}, CO_3^{--}, and Na^{+} (Piper, 1942); pH saturated paste, cation exchange capacity, and gypsum (Richards *et al.*, 1954); Ca^{++} (Hutton, 1954); and Mg^{++} (Tucker and Bond, 1954).

For laboratory tests on base unsaturated soils an acid sample of the A horizon of Hanwood Sandy Loam, a widespread soil type of the area, was leached with $CaCl_2$, pH 4·1. At the end of leaching this sample was 70 per cent. base unsaturated and contained 30 per cent. exchangeable Ca^{++}. Subsamples were then treated with $Ca(OH)_2$ and NaOH to obtain series of samples with three different degrees of base saturation. These series were low Ca^{++}: 30 per cent. exchangeable, medium Ca^{++}: 50 per cent., and high Ca^{++}: 80 per cent. Each series consisted of samples with 0, 5, 10, 15, 20, and 30 per cent. exchangeable Na^{+}. Hydraulic conductivity and percentage dispersion were determined according to Richards *et al.* (1954).

The classification of Richards *et al.* (1954) for salty soils into saline and saline–alkali soils is used. In this classification both saline and saline–alkali soils have an electrical conductivity of the saturation extract

greater than 4 mmhos/cm. However, saline soils contain less and saline–alkali soils more than 15 per cent. exchangeable Na^+. The terms soluble Na^+ percentage, soluble Ca^{++} percentage, &c., refer to the proportion of the individual cations or anions in relation to the total ion concentration (all values expressed in m.e./l.).

Results and Discussion

For convenience a general description of the data is given first, followed by a discussion of the composition of some typical profiles (Table 2, page 137).

(*a*) *General description of results*

I. *Anion composition.* In the 1:5 soil-water extracts of the majority of profiles Cl^- was the predominant anion. Chloride as a percentage of

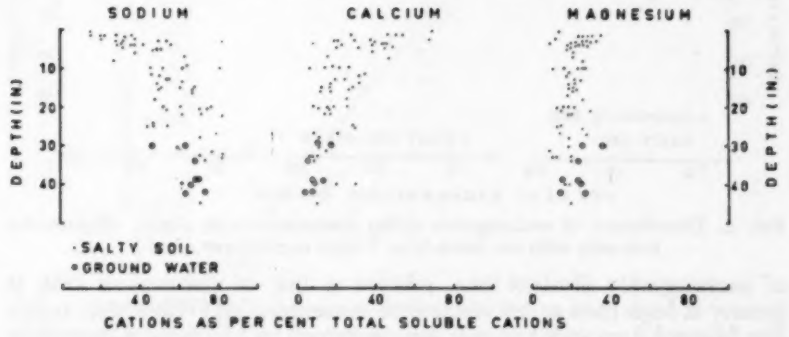

FIG. 1. Distribution of soluble cation percentages with depth.

the total anions varied between 30 and 90. The Cl^- percentage of the saturation extract of the A horizon was generally higher than that of the 1:5 soil-water extract, and varied between 70 and 90 in most cases. The few exceptions were found in only slightly salty profiles. This higher Cl^- percentage of the saturation extract, as compared with the 1:5 soil-water extract, was apparently due to the low solubility of gypsum.

In the saturation extracts of the A horizons HCO_3^- varied between 0·3 and 4·1 m.e./l. It usually increased slightly with depth. CO_3^- was found only in a few subsoil samples which also contained high amounts of exchangeable Na^+. The amount varied between 0 and 3 m.e./l. Higher amounts of HCO_3^- and CO_3^- occurred in the groundwater than in the saturation extracts. In the groundwater HCO_3^- varied between 4·9 and 21 m.e./l. and CO_3^- between 0 and 9·3 m.e./l.

II. *Cation composition of the saturation extract.* The soluble Ca^{++}, Mg^{++}, and Na^+ percentages of the groundwater and of the saturation extracts from samples taken at different depths are presented in Fig. 1.

In the majority of profiles the soluble Na^+ percentage increased with depth while the soluble Ca^{++} percentage decreased with depth. No

significant change was found for the soluble Mg^{++} percentage, but different distribution patterns were found for different profiles.

It is of interest to note that the cation composition was fairly uniform at lower depths, Na^{+} exceeded Mg^{++} and Mg^{++} was present in larger amounts than Ca^{++}. A higher variability occurred in the surface layers, and some reasons for this phenomenon will be discussed later.

Much smaller amounts of K^{+} than of other ions occurred in the saturation extracts, and this is in agreement with results for other areas (Richards *et al.*, 1954). These low soluble K^{+} contents are, naturally, partly due to the lower amounts of exchangeable K^{+} than of divalent ions. Another contributing factor would be the general rule that release

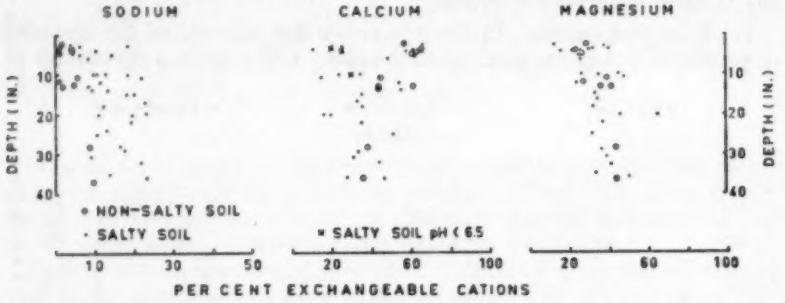

FIG. 2. Distribution of exchangeable cation percentages with depth. (Figures for non-salty soils are taken from Taylor and Hooper, 1938.)

of exchangeable divalent ions, relative to that of monovalent ions, is greater at high than at low electrolyte concentrations (Wiklander, 1955). For Mirrool Area soils this rule was confirmed by additions of increasing amounts of NH_4Cl (Groenewegen and Bouma, 1960), and of NaCl (unpublished data). It was found that at high electrolyte concentrations the soluble Ca^{++}/K^{+} ratio exceeded the exchangeable Ca^{++}/K^{+} ratio.

III. *Exchangeable cations.* The exchangeable cation percentage of the salty soils are compared in Fig. 2 with those for the non-salty soils.

In the majority of salty profiles both exchangeable Ca^{++} and Mg^{++} percentages[1] were similar to those of the non-salty profiles. In both salty and non-salty soils exchangeable Ca^{++} decreased and exchangeable Mg^{++} increased as a rule with depth. The only distinct difference in most cases was a higher exchangeable Na^{+} percentage in the salty soils. Even so the exchangeable Na^{+} percentage of samples from the 0–10 in. layer was usually not higher than 10, a low figure for salty soils. Below a depth of 10 in. higher amounts of exchangeable Na^{+} occurred, but there was no further change with depth.

IV. *Relation between soluble and exchangeable ions.* The exchangeable Na^{+} percentage is both dependent on the total cation concentration, and on the relative proportion of the soluble cations. Empirically, Richards *et al.* (1954) found that the relationship between soluble and exchangeable cations in salty soils was best expressed by the use of the Sodium

[1] The three acid profiles were, naturally, excluded from the consideration on Ca^{++}.

Adsorption Ratio (SAR) and the Exchangeable Sodium Ratio (ESR). The SAR refers to the soluble phase and is defined as:

$$SAR = \frac{Na^{+}}{\sqrt{\{\frac{1}{2}(Ca^{++}+Mg^{++})\}}}, \quad (1)$$

all ions expressed as m.e./l.

The ESR refers to the exchangeable cations and is defined as:

$$ESR = \frac{\text{exch. } Na^{+} \text{ (m.e./100 g.)}}{\text{cation exchange capacity} - \text{exch. } Na^{+} \text{ (m.e./100 g.)}}. \quad (2)$$

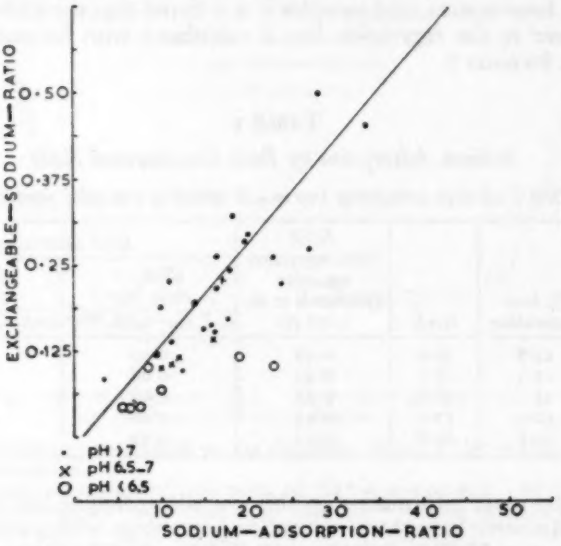

FIG. 3. Relation between Sodium Adsorption Ratio and Exchangeable Sodium Ratio. (The regression line of Richards *et al.*, 1954, is included for comparison.)

The relationship between SAR and ESR for local soils is shown in Fig. 3, the regression line of Richards *et al.* (1954) is included for comparison. It is shown that the relation was very good for all profiles with a pH over 6·5, and about similar to that of Richards *et al.* This is of particular interest because two different methods to determine exchangeable Na^{+} were used. Richards *et al.* determined the exchangeable Na^{+} by subtracting the Na^{+} of the saturation extract from total extractable Na^{+}. In the present investigation exchangeable Na^{+} was determined by removal of Cl^{-} from the sample with 60 per cent. alcohol, prior to the extraction of exchangeable cations with NH_4Cl.

V. *Sodium adsorption in base unsaturated soils.* It is also shown in Fig. 3 that samples of low pH had a lower ESR than expected from the SAR. This tendency was especially strong in the A horizon of soils with a pH below 6·5.

It should be noted that Richards *et al.* developed the relation between SAR and ESR on neutral and alkaline soil samples.

In such base saturated samples both the SAR and ESR express the proportions of Na^+ and of divalent ions. In acid samples, however, the divisor of the ESR (formula 2) consists partly of exchangeable H^+ or Al^{+++} (Russell, 1950). For such acid samples the ESR would perhaps be better defined by:

$$\frac{\text{exch. } Na^+ \text{ (m.e./100 g.)}}{\text{exch. } (Ca^{++} + Mg^{++}) \text{ (m.e./100 g.)}}. \qquad (3)$$

For the base unsaturated samples it was found that the ESR values lie much closer to the regression line if calculated with formula 3 rather than with formula 2.

TABLE 1

Sodium Adsorption by Base Unsaturated Soils

(NaCl *solutions containing 100 m.e./l. added to non-salty samples*)

Sample	% *base saturation*	*SAR*	*ESR from regression equation (Richards* et al. *(1954))*	*ESR determined*	
				$ESR_2 = \frac{exch.\ Na^+}{C.E.C. - exch.\ Na^+}$	$ESR_3 = \frac{exch.\ Na^+}{exch.\ Ca^{++} + Mg^{++}}$
A	14·8	32·9	0·48	0·09	0·54
B	15·3	28·5	0·42	0·08	0·52
C	44·1	16·3	0·23	0·08	0·20
D	50·9	17·0	0·24	0·08	0·17
E	74·5	15·8	0·22	0·12	0·17

To obtain more information on this low adsorption of Na^+ some non-salty profiles were brought to saturation percentage with a solution containing 100 m.e. NaCl/l. It is shown in Table 1 that the determined ESR (calculated according to formula 2) was again considerably less than the ESR calculated from the regression equation. The discrepancy became particularly large in the soils which had a base saturation of only 15 per cent. The discrepancy was considerably less if the ESR was calculated according to formula 3, although it was still fairly large in profiles D and E.

VI. *Hydraulic conductivity as related to degree of* Na^+ *and base saturation.* It was of interest to establish whether the degree of base saturation influenced the dispersing effect of Na^+. The hydraulic conductivity and the percent. dispersed clay of three series of samples, with different degrees of base saturation were determined (Fig. 4). In Fig. 4 the hydraulic conductivities are recorded as a percentage of the values for samples not containing Na^+. In all Ca^{++} series hydraulic conductivity was reduced in the presence of 5 per cent. exchangeable Na^+, and it rapidly declined to very low values at the higher exchangeable Na^+ levels. The reduction in hydraulic conductivity at the 5 per cent. exchangeable Na^+ level, was independent of the degree of base satura-

tion. At the higher exchangeable Na^+ levels decreases in hydraulic conductivity were greater in the low than in the medium and high Ca^{++} series.

The hydraulic conductivities of soils with similar levels of exchangeable Na^+ (ESR formula 2) were thus dependent on degree of base saturation. There was also no direct relationship between hydraulic conductivity and the ESR of formula 3. Samples with similar values for ESR (formula 3) were: Ca^{++} 30, Na^+ 10, and Ca^{++} 80, Na^+ 30; also

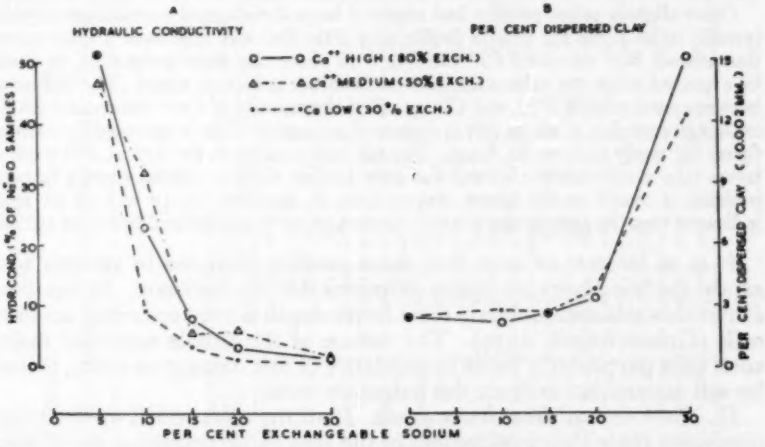
A
HYDRAULIC CONDUCTIVITY
B
PER CENT DISPERSED CLAY
O—O Ca++ HIGH (80% EXCH.)
Δ--Δ Ca++ MEDIUM (50% EXCH.)
•---• Ca LOW (30 % EXCH.)
HYDR. COND. (% OF Na=0 SAMPLES)
PER CENT DISPERSED CLAY (<0.002 MM.)
0 5 10 15 20 30
PER CENT EXCHANGEABLE SODIUM

FIG. 4. Laboratory experiments on the dispersing effect of Na^+ at different degrees of base unsaturation.

A. Hydraulic conductivity (per cent. of $Na^+ = 0$ samples). At $Na^+ = 0$ the hydraulic conductivities in cm./hour were: high $Ca^{++} = 0{\cdot}88$; medium $Ca^{++} = 1{\cdot}1$; low $Ca^{++} = 1{\cdot}48$.

B. Percent. dispersed clay at high and low Ca^{++}.

Ca^{++} 50, Na^+ 10 and Ca^{++} 80, Na^+ 15. Yet in both cases the base unsaturated samples had four times as high a hydraulic conductivity as the base saturated samples with similar exchangeable Na^+/Ca^{++} ratios.

It should be noted that, in the soils with 0 and 5 per cent. exchangeable Na^+, base unsaturated samples had much higher actual hydraulic conductivities than the base saturated samples. At the higher exchangeable Na^+ levels the actual hydraulic conductivities were nearly the same for the three Ca^{++} series.

The percentage of dispersed clay was not affected by the degree of base saturation. In this determination only 30 per cent. exchangeable Na^+ showed a strong dispersing effect.

(*b*) *Source of salts accumulated in the surface layers*

I. *Salts derived from the irrigation water.* The quality of the irrigation water in the Murrumbidgee Irrigation Areas is one of the highest in the world. Richards *et al.* (1954) state that water with 2½ times the salt

concentration still does not give a salinity hazard, except on soils of extremely low permeability.

It does seem likely, however, that salts in some slightly saline profiles of the Mirrool Area were derived from the irrigation water.

An example is profile 8 in Table 2. The sandy surface layers of this profile (0–5 and 6–8 in. depth) contained about equal quantities of Ca^{++} and Mg^{++}. Both Cl^- and SO_4^{--} occurred in about double the Ca^{++} and Mg^{++} concentrations. This composition is very similar to that of the irrigation water, once HCO_3^- has precipitated. Na^+ is lower than in the irrigation water but this could but due to cation exchange.

Other slightly saline profiles had received large dressings of ammonium sulphate (profile 10 in Table 2). In this profile very little Na^+ was adsorbed. In the saturation extract Na^+ exceeded Cl^- and Mg^{++} in about the same proportion as would be expected when the salts were derived from the irrigation water. The difference between total soluble SO_4^{--} and Cl^- equalled the amount of Ca^{++} removed from the exchange complex when an initial degree of saturation of 80 is assumed (a common figure for sandy soils in the Area). The salt composition in the 0–7 in. and 7–16 in. layers (the sandy surface layers) was very similar while a sudden change in composition is found in the heavy, impervious, B_1 horizon (19–42 in.). This again indicated that the salts in the 0–16 in. layer had not been derived from the subsoil.

It is of interest to note that these profiles occurred in an area with sandy surface layers on heavy impermeable B_1 horizons. It has been found that salt accumulation from lower depth is very restricted on these soils (Groenewegen, 1959). The nature of the profile naturally makes such soils particularly liable to incidence of salt damage to crops, caused by salt accumulation from the irrigation water.

II. *Salts derived from lower depth.* If all the salts added in the irrigation water since the development of the area had remained in the surface 12 in., then 10 m.e. Cl^-/1,000 g. soils would have accumulated (Groenewegen, 1959).

As shown in Table 2 most salty soils contain much higher amounts of Cl^- in this layer (profiles 9, 13, 20, and 22). Only four of the twenty-three profiles used in this study had sufficiently low Cl^- contents to make the irrigation water the likely source of the accumulated salts. If the salts were derived from the irrigation water one would further expect that Cl^- would equal the SO_4^{--} soluble in the 1:5 extract. In many profiles, however, Cl^- exceeded SO_4^{--} (e.g. profiles 14, 20, and 22). Finally, high amounts of Cl^- in the surface layers of the Mirrool Area were associated with high amounts of Cl^- at greater depth. The correlation coefficient in one area with a high watertable was 0·66 for forty-three profiles. From these observations it is certain that, in the more saline profiles, the larger part of the soluble salts in the surface soil layers was derived from salts initially present at greater depth.

(c) *Composition of some typical profiles*

I. *Surface soils high in divalent ions.* When salts from lower layers, consisting largely of Na^+, accumulate in the non-salty surface layers of a soil cation exchange will tend to decrease the soluble Na^+ percentage and increase the proportion of soluble divalent ions, particularly of Ca^{++} (Kelley, 1951). The majority of profiles showed this decrease in soluble

TABLE 2

Composition of Saturation Extract and of Exchangeable Cations of Some Typical Profiles

Profile and soil type	*Depth*	*Saturation percentage*	*pH saturated paste*	*m.e. gypsum/1,000 g. of soil not soluble in saturation extract*	*Ions saturation extract m.e./l.*								*Cation exchange capacity m.e./100 g.*	*% exchangeable cations*			
					Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Cl^{-}	SO_4^{--}	HCO_3^{-}	CO_3^{--}		Ca^{++}	Mg^{++}	Na^{+}	K^{+}
8 Yambil Sandy Loam	0–5	26	7·2	0	12·3	9·7	11·0	..	19·0	16·2	1·4	0	11	..	..	7·8	..
	6–8	24	8·1	0	2·1	2·6	7·9	..	5·5	6·4	1·1	0	..	..	..	..	..
	12–18	50	8·0	..	1·2	1·8	6·3	..	3·1	4·3	1·3	0	..	..	..	..	..
	30–36	64	8·6	..	0·8	1·2	9·0	..	2·4	4·3	3·6	0	..	..	..	..	..
9 Yenda Sandy Loam	0–7	23	8·0	141·0	40·9	48·0	410·0	..	440·0	87·7	4·2	0	13·4	10·9	40·7	39·4	18
	7–14	28	8·3	8·2	6·4	10·8	82·2	..	77·7	20·6	3·4	0	12·6	15·8	48·0	21·8	16
	14–26	57	8·1	2·4	5·4	10·9	50·8	..	52·4	14·1	2·9	0	24·9	16·3	45·6	23·4	18
10 Hyandra Sandy Loam	0–7	29	5·6	18·7	26·5	14·8	25·4	..	17·8	44·3	0·3	0	11·6	20·4	30·6	4·2	4
	7–16	25	5·1	9·7	21·0	11·2	27·3	..	20·8	35·8	0·17	0	..	..	..	..	..
	19–42	46	7·7	..	6·2	7·3	38·9	..	21·6	22·5	1·6	0	22·8	34·1	42·5	10·1	8
13 Hanwood Sandy Loam	0–8	36	6·2	51·3	60·7	51·9	143·3	..	194·0	51·9	0·5	0	20·9	25·6	31·7	10·7	7
	8–12	50	6·6	18·8	22·1	20·1	72·9	..	68·3	51·4	0·5	0	27·5	30·8	26·1	13·5	4
	12–21	58	7·3	..	22·8	23·9	89·2	..	79·0	58·5	0·9	0	33·5	36·6	33·7	23·6	6
	21–42	56	8·0	..	12·1	6·6	60·9	..	51·9	26·3	1·6	0	27·2	42·8	41·6	22·2	5
14 Tharbogang Loam	0–5	25	8·0	2·3	51·4	40·3	350·0	2·3	350·0	102·4	3·3	0	17·2	37·1	21·4	32·8	..
	5–15	33	8·1	0·7	1·8	2·0	44·9	0·3	38·0	8·6	1·7	0·8	15·0	34·1	32·9	28·2	..
	15–33	42	8·4	..	0·8	1·9	33·0	..	27·6	4·6	2·2	0·9	..	32·4	27·2	33·3	..
20 Yenda Clay Loam	0–8	37	6·8	28·2	113·7	63·8	72·5	5·0	224·0	28·1	2·3	0	19·1	57·6	26·1	4·4	8
	8–12	41	6·6	2·9	43·2	42·4	73·4	1·5	118·0	39·3	1·9	0	22·5	34·4	37·1	10·9	6
	12–16	57	7·8	..	20·9	24·3	72·0	..	75·4	38·4	2·3	0	29·9	..	..	13·6	..
	16–39	60	8·2	..	4·1	8·3	46·4	..	38·4	19·9	3·3	0	..	..	..	..	..
22 Mallee C	0–12	61	7·8	2·2	140·4	76·5	142·9	1·2	349·0	14·3	1·5	0	37·5	47·4	26·8	8·8	11
	12–24	58	7·9	2·1	67·0	65·5	123·0	0·3	239·0	17·1	1·0	0	..	..	..	..	..
	24–30	51	8·0	..	47·4	64·4	117·6	..	198·0	14·7	1·1	0	32·6	37·0	32·9	12·6	7

Na^+ percentage and increase of soluble Ca^{++} percentage upon salt accumulation in the surface layers (Fig. 1, see also profile 22 in Table 2). These soils were saline soils according to the classification of Richards *et al.* (1954). If this was the only change in salt composition it would not be expected that the variability in composition of the saturation extracts of the subsoil and surface layers would be markedly different. This applies particularly in an area where the cation exchange capacity

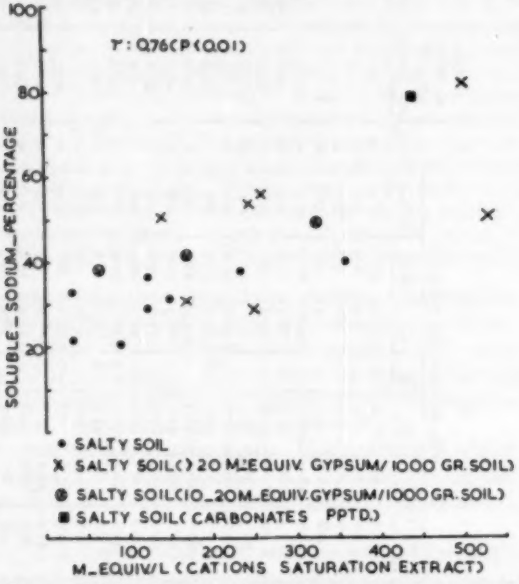

FIG. 5. Relation between the cation content of saturation-extract and the soluble sodium percentage (A horizon of field samples.)

is fairly uniform for most soils. As shown in Fig. 1 the variability in the extracts of the surface layers was distinctly higher than of the subsoil layers. This increase in variability was apparently mainly caused by the precipitation of divalent ions, as gypsum or carbonates, in some profiles.

II. *Soils in which divalent ions had precipitated.* As precipitation of divalent ions occurs especially at high salt concentration the soluble Na^+ percentage tends to increase with increasing salt concentration (Richards *et al.* 1954). For Mirrool Area soils this increase of the soluble Na^+ percentage is shown in Fig. 5. It can also be seen from this figure that most soils containing gypsum had a higher soluble Na^+ percentage than soils of similar salt concentration not containing gypsum.

The two profiles[1] in which large amounts of gypsum had precipitated during salt accumulation (e.g. profile 9, Table 2) contained high amounts of soluble and exchangeable Na^+. In these saline–alkali soils soluble and

[1] No fertilizer had ever been applied to these profiles.

exchangeable Ca^{++} were medium to very low. Exchangeable Mg^{++} exceeded exchangeable Ca^{++}.

Profile 14 is the only soil in which the occurrence of considerable precipitation of carbonates is highly likely. This is indicated by the presence of carbonates in A and B_1 horizons of this salty profile, while these horizons of the adjacent normal soil were slightly acid. Soluble Ca^{++} and Mg^{++} were low, and soluble and exchangeable Na^{+} were high. The groundwater of this saline–alkali profile had 10 m.e./l. of residual carbonates, while no other groundwater analysed contained residual carbonates. Kelley (1951) states that in some areas of California saline soils are found near saline–alkali soils not containing gypsum. He suggested that such differences were presumably due to variations in the composition of the groundwater.

III. *Soils which had received heavy dressings of fertilizer.* Two of the soils which contained gypsum had a high soluble Ca^{++} and a low soluble Na^{+} percentage in the A horizon (e.g. profile 20 in Table 2). These saline soils had received heavy dressings of superphosphate. All other characteristics were similar to the soils in which no gypsum occurred and it can be safely assumed that the gypsum had been derived from the fertilizer.

Two other soil profiles were influenced by ammonium sulphate applications (e.g. profile 13, Table 2). In the A horizon they had a relatively low pH (6·2 and 5·5), and contained high amounts of gypsum. The soluble Na^{+} percentage was rather high and the soluble Ca^{++} percentage rather low. These saline soils thus had a fairly similar composition to the saline–alkali soils in which gypsum had precipitated during salt accumulation. The only major difference was the low exchangeable Na^{+} percentage.

General Discussion

(*a*) *Changes upon salt accumulation in the surface.* It has been stated earlier that the irrigation water, used in the Mirrool Area, is of a high quality and that the surface soils were originally non-calcareous and did not contain gypsum. It is thus one of the few irrigation areas in which it is reasonably certain that the greater part of the salts have accumulated from lower soil layers, and that any salts of low solubility have been formed during salt accumulation. Under these conditions the changes in soluble and exchangeable ions upon salt accumulation followed trends, which would be expected from laboratory studies as reported by Kelley (1951).

In the Mirrool Area the lower soil layers had a high soluble Na^{+} percentage (Fig. 1). The equilibrium between soluble and exchangeable cations often resulted in exchangeable Na^{+} values of 15 per cent. or higher (Fig. 2). During salt accumulation in the surface layers cation exchange usually resulted in an increase of the soluble Ca^{++} and a decrease of the soluble Na^{+} percentage. In these cases saline soils were invariably formed. The exceptions were profiles in which considerable quantities of gypsum or carbonates precipitated, then saline–alkali soils were formed (Table 2, profiles 9 and 14).

It should be noted that the formation of salty soils will be distinctly

different when salt accumulation is caused by application of saline irrigation water, or by flooding of the sea. Scofield (1941), for example, studied the salty soils of the Pecos River Area. As stated earlier the Pecos River has a high salinity content. Scofield's data indicate that the average soluble Na^+ percentage of the soils did not change markedly with depth; this is in contrast to the results obtained in the present investigation (see Fig. 1). If the water is applied to the surface the divalent ions, released from the surface soil, tend to be leached to lower soil layers. The chances of saline–alkali soil formation are, therefore, also much greater than in the case of salt accumulation from lower depth. Van den Berg (1952), for example, found that the dilution of sea with river water resulted in a Na^+ percentage of 70–80. This value is very similar to the soluble Na^+ percentage of the lower soil layers described in the present paper. However, in van den Berg's case flooding with water of this composition resulted in the widespread formation of saline–alkali soils.

(*b*) *Base unsaturated soils and their relevance to the classification of salty soils.* It should be noted that salt accumulation in base unsaturated soils will not always result in the formation of saline, base unsaturated, soils. If the accumulating salts should contain considerable amounts of carbonates these would tend to correct excess soil acidity, and base saturated soils would be formed. Whether the soils would become saline or saline–alkali will depend on the proportion of mono and divalent cations in the accumulating salts. The saline, base unsaturated, soils described in this paper will only be formed if the accumulating salts are mainly neutral.

It has been shown that the sodium adsorption of base unsaturated soils is much lower than that of base saturated soils. Hissink (1924) was one of the first to draw attention to the fact that H^+ is very strongly adsorbed by the exchange complex of the soil. The low Na^+ adsorption in base unsaturated soils is apparently another expression of this phenomenon.

In the laboratory tests the dispersing effect of Na^+ was only in certain instances dependent on the degree of base saturation. When the exchangeable Na^+ percentage was 10 or more the reduction in hydraulic conductivity was larger for the samples with the highest degree of base unsaturation. Martin and Richards (1959) also found that Na^+ and NH_4^+ reduced hydraulic conductivity more in base unsaturated than in base saturated samples. It should be noted that in the present investigation no effect of base saturation was found at the 5 per cent. exchangeable Na^+ level, nor was the degree of dispersion affected by base saturation. Further detailed study will be required to clarify this complex interaction between degree of base and Na^+ saturation.

The base unsaturated saline soils are of relevance to the classification of salty soils. The field samples had less than 15 per cent. exchangeable Na^+, and they are thus saline soils according to the classification of Richards *et al.* (1954). The base unsaturated saline soils have, however, a high soluble Na^+ percentage, and in this characteristic they are similar to saline–alkali soils.

A new classification of salty soils would require more information on the dispersion of base unsaturated as well as base saturated soils. In the

present classification a soil is classified as saline–alkali when it contains 15 or more per cent. exchangeable Na^+. Yet, Aldrich *et al.* (1945) found severe dispersion in a citrus orchard soil with only 10 per cent. exchangeable Na^+. The disturbed samples in the present investigation also showed a strong reduction in permeability at this exchangeable Na^+ level. It is suggested that in the future classification of salty soils it might well be advisable to replace, or to supplement, the percentage exchangeable Na^+ measurement with a soil physical test.

Acknowledgements

The author wishes to thank Miss E. J. Nairne, C.S.I.R.O., Griffith, and Mr. H. Meyer, previously C.S.I.R.O., Griffith, for their technical assistance.

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THE PREPARATION AND STUDY OF THIN SECTIONS OF WET ORGANIC SOILS MATERIALS[1]

A. F. MACKENZIE and J. E. DAWSON[2]

(WITH PLATES 1–4)

Summary

Thin sections of wet samples of disintegrated peats, sedimentary peats, and mucks were prepared in Carbowax 6000. Conventional methods of thin section preparation following freeze drying of the samples were not suitable for the study of organic soils because of organic matter shrinkage. Microscopic examination of Carbowax sections revealed numerous blobs of organic matter about 0·02 mm. in diameter in sedimentary peats. These blobs are presumably fecal pellets evacuated by small aquatic animals. Disintegrated peats contained variable amounts of plant fragments showing cellular structure. Muck soils were highly granulated, and the granules were small compared with the upper size limit of very fine sand.

THE physical structure of organic soil horizons *in situ* is important in studying the genesis of horizons as well as in identifying horizons observed in the field. Unfortunately, the high water content of these materials in their natural state combined with a large change in volume upon drying of some of the materials, renders the normal processes of thin section preparation inadequate. Drying of organic soil samples often causes irreversible alteration of the structure because of shrinkage of the organic matter.

Kubiena (1953) illustrated some thin section preparations of an old Sphagnum peat moor, raw humus, and raw soil humus. The old Sphagnum peat thin section showed slightly decomposed moss remains impregnated with acid humus sols, while the raw humus section showed accumulations of little decomposed plant remains. The methods for preparation of the thin sections were not given. Sedimentary peat was suspended in a water drop and the detritus of droppings of small animals, residues of animals, insects, plants, and shells of diatoms were observed.

Mitchell (1956) developed a method for preparing thin sections of clays at natural water contents as the use of dry samples was undesirable. The soil moisture was replaced with a high molecular weight polyethylene glycol compound (Carbowax 6000).[3] This material is hard at room temperature; melts at about 55° C., and is soluble in water in all proportions. The effects of water replacement by Carbowax on the clay were believed to be negligible as no volume changes were observed on treatment. It was felt that the thin sections thus produced gave an accurate picture of the fabrics of the clays studied. Application of this

[1] Contribution from the Agronomy Department, Cornell University, Ithaca, New York. Part of a thesis submitted by the senior author in partial fulfilment of the requirements for the Ph.D. degree (Agronomy paper no. 507).

[2] Assistant Professor, Department of Soils, Ontario Agricultural College, Guelph, Ontario, Canada, and Professor of Soil Science, Agronomy Department, Cornell University, Ithaca, New York respectively.

[3] Union Carbide Chemical Co., New York, N.Y.

method to the processing of thin sections of organic materials offered a possibility for reducing the rather drastic effect of drying on the structure of the organic soil.

Materials and Methods

Soil samples

Samples of sedimentary peats, disintegrated peats, and muck soils were used in this study. Several of the sedimentary peats contained large numbers of diatom skeletons. The muck soils were distinguished by having a solubility in saturated sodium pyrophosphate equivalent to more than a 0·75 per cent. reference peat solution. Samples were obtained from New York, Michigan, Minnesota, and Washington, and preserved at field moisture conditions.

Thin section preparation using Carbowax

The Carbowax was melted at 70° C. and poured into aluminum weighing dishes where it remained in liquid form in an oven set at 60° C. The peat samples were placed in the Carbowax. After three days the dishes were removed from the oven, and the Carbowax was allowed to solidify.

For grinding and polishing only fine grained silicon carbide (no. 600)[1] was used, as the Carbowax was readily polished. Kerosene was used as the lubricant. However, as a final operation, the Carbowax sections were polished using only kerosene and a piece of plate glass that had been slightly etched from a previous polishing. This was necessary to remove silicon carbide particles that tended to adhere to the Carbowax. A section of the hardened Carbowax containing the organic matter was polished on one side and glued to a microscope slide with Duco cement. The other side was then ground and polished to the desired thickness.

Thin section preparation using resin

The organic samples were frozen in a dry ice-acetone bath and then lyophilized.[2] The dry samples were then sectioned by the conventional methods using a thermal setting polyester resin, Bioplastic,[3] and silicon carbide as the grinding compound.

Results and Discussion

Preliminary studies on the preparation of thin sections of organic soils were carried out using samples of sedimentary peats containing a high proportion of diatoms. These peats were selected because any drying of the sample caused irreversible shrinkage of the organic matter, exposing the diatom masses. The samples thus served as a very sensitive indicator of the effectiveness of techniques in preserving the original structure.

Thin section preparations of a sedimentary peat high in diatoms are shown in Plates I and II. Plate I illustrates the lyophilized sample imbedded in Bioplastic. The organic matter has shrunk into small

[1] Carborundum Company, Niagara Falls, New York.

[2] Lyophilization is the process of low temperature drying under high vacuum conditions, commonly called 'freeze-drying'.

[3] Ward's Natural Science Establishment, Inc., Rochester, New York.

particles and strands or layers in a matrix of diatoms. A similar sample prepared after oven-drying at 105° C. exhibited the same organic matter structure. Lyophilization seems unsuitable for the pretreatment of organic matter prior to thin section preparation.

When the sample was imbedded in Carbowax as shown in Plate II the organic matter remained as amorphous blobs of material. The diatoms were in a matrix of organic matter. This method seemed to be suitable for preparing thin sections of organic soils and was subsequently used in the study of other samples of sedimentary peat, disintegrated peat and muck.

The sedimentary peat samples were all very similar in appearance to the sample shown in Plate II, in which small blobs of organic matter are seen on a background of detritus. The following phrases that occur in published descriptions of peat apply very well to Plate II: Rigg (1958), 'fecal pellets'; Kubiena (1953) and Rigg (1958), 'excretal balls of aquatic animals' together with 'detritus of droppings of small soil animals'. The size of the fecal pellets observed in Plate II, approximately 0·02 mm. in diameter, indicates that they were produced by the smaller aquatic animals as suggested by Rigg (1958). Highly diatomaceous sedimentary peats when dried become paler in colour because shrinkage of the organic matter reveals the presence of the diatoms.

A disintegrated peat sample is illustrated in Plate III. Many fragments of plant material are visible in this sample that exhibit cellular structure. A considerable amount of detritus that does not exhibit cellular structure is also visible. Aggregates are not present but other more disintegrated peat samples showed a tendency towards aggregation and a structure more like muck samples.

All the muck samples prepared were similar to the one illustrated in Plate IV. The organic matter was very dark brown in colour, as a result of the accumulation of brown acids on oxidation. Muck soils also exhibited a high degree of aggregation, probably because of microbial polysaccharides gums and mucilages as well as other decomposition products.

The samples observed in this study indicate that the physically disintegrated sample shown in Plate III, and the completely disintegrated and highly oxidized sample shown in Plate IV are members in a continuum of samples from dead plant materials to fully disintegrated and highly oxidized organic soil samples. These samples also indicate that aggregation is generally more complete and more highly developed in muck than in disintegrated peat, but that this test alone is not an adequate distinction between these two materials.

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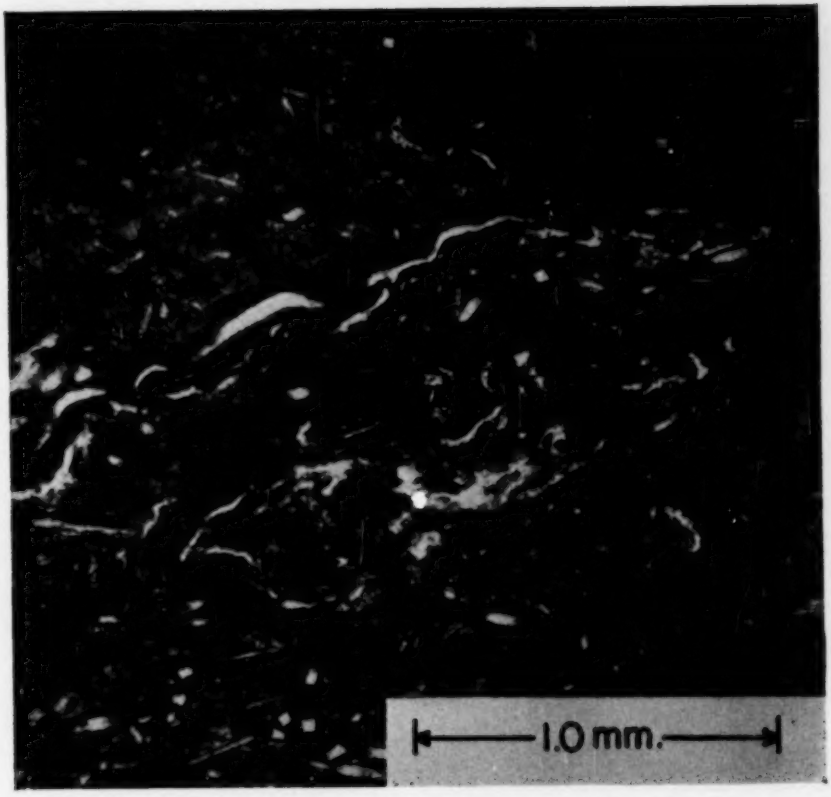
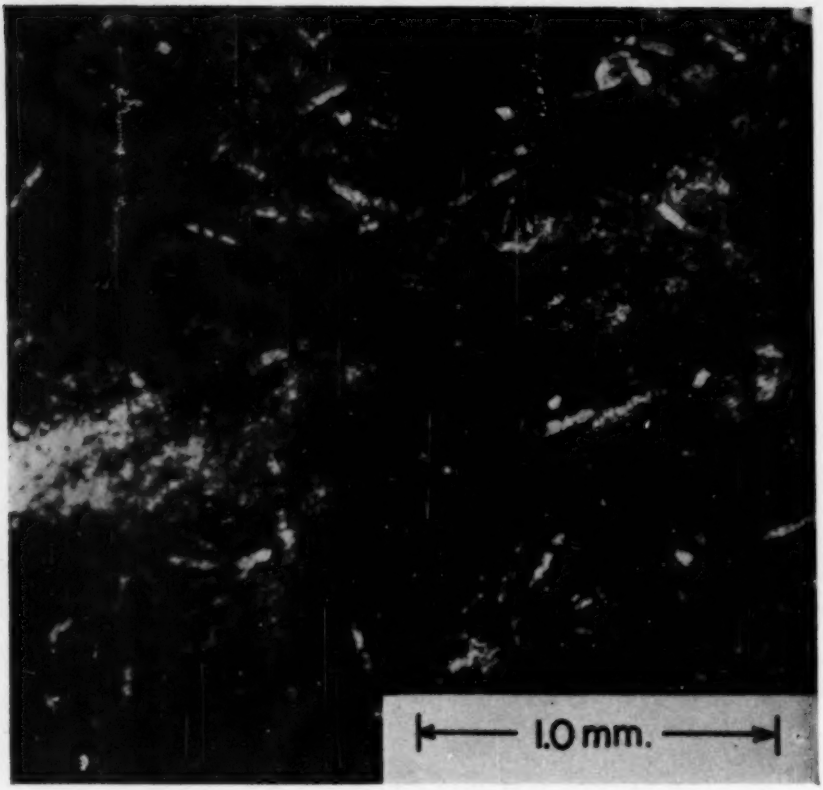


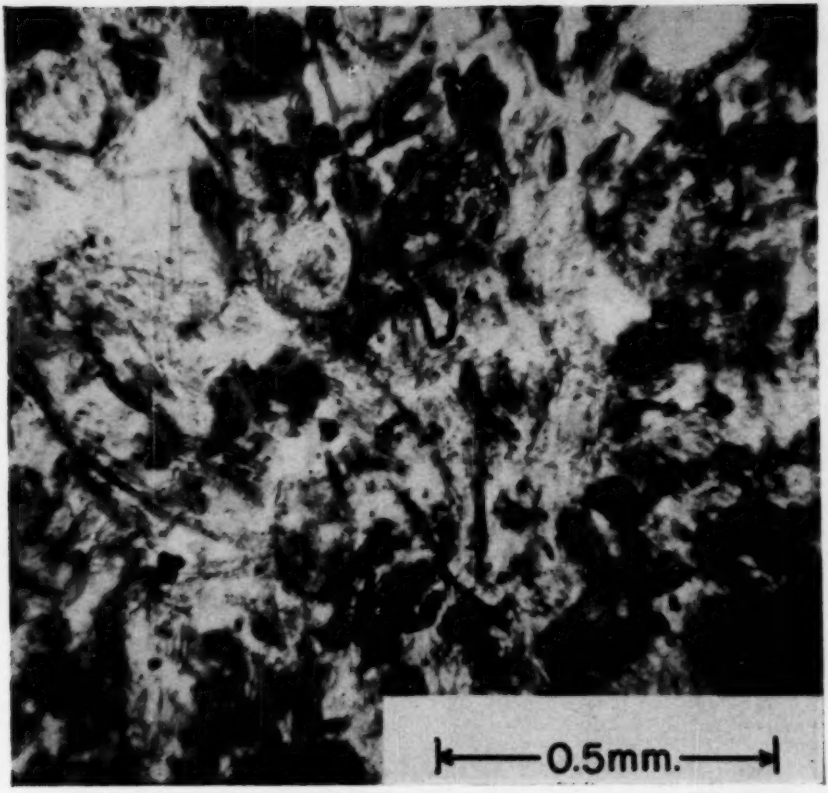
A thin section of a lyophilized sample of sedimentary peat high in diatoms and cast in Bioplastic.

A. F. MACKENZIE *and* J. E. DAWSON—PLATE I.



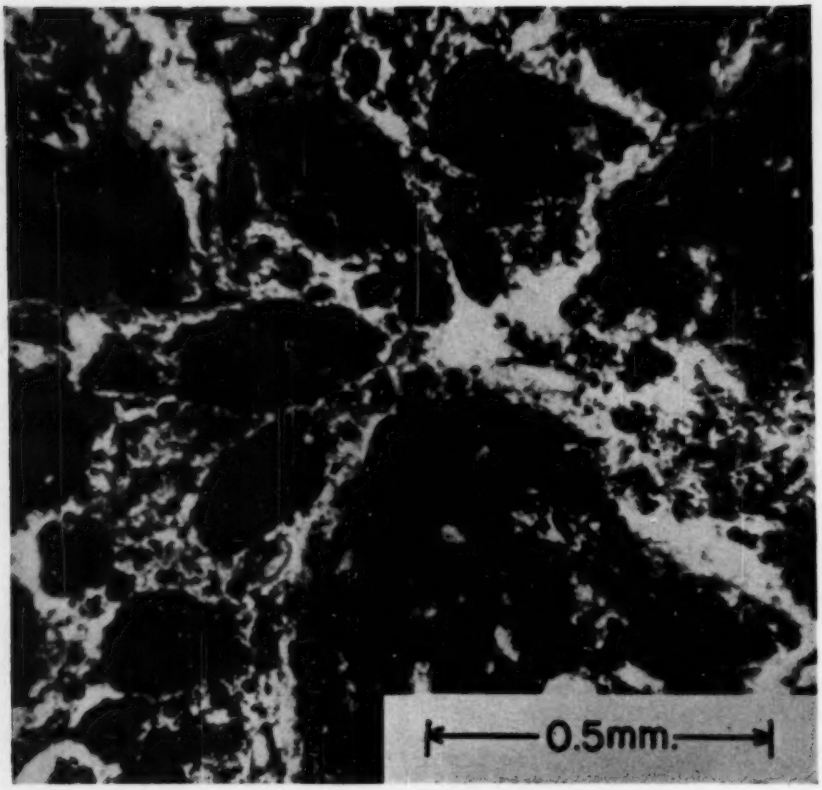
A thin section of wet sample of sedimentary peat high in diatoms and cast in Carbowax 6000.

A. F. MACKENZIE *and* J. E. DAWSON—PLATE II.



A thin section of a wet sample of disintegrated peat cast in Carbowax 6000.

A. F. MACKENZIE *and* J. E. DAWSON—PLATE III.



A thin section of a wet sample of muck cast in Carbowax 6000.

A. F. MACKENZIE *and* J. E. DAWSON—PLATE IV.

THE MICROSCOPY OF THE SILT FRACTION

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Summary

The microscopy of silt and very fine sand yields valuable information if the relevant petrological techniques are appropriately modified. The applicability of wire- and nylon-sieving, sedimentation, panning, heavy-liquid separation, and staining to fine materials is considered. A method of passing through tin foil perforated with slits a few microns wide classifies material by thickness and not by real or nominal diameters, thus giving micro-preparations with all the material near the same level of focus. The importance of dispersion when mounting and choice of correct cover-glass thickness is discussed. A method of assessing densities of the particles in heavy liquids under the microscope is described and precautions necessary for obtaining the maximum amount of information from the examination with polarized light and phase contrast are outlined.

Introduction

THE nature of the clay fraction and of the sand fraction of soil is now fairly well understood, the former because it is amenable to study by certain relatively modern techniques such as X-ray diffraction and electron microscopy and the latter because it is of convenient particle size for study by well-established methods involving the use of the polarizing microscope. On the other hand, our knowledge of the silt fraction remains, in general, unsatisfactory, although silt-size mineral material is certainly of great pedological interest. It may consist largely of unstable minerals which because of their size and physical conditions are a more ready source of plant nutrients than the sand-size material and may also contain stable minerals providing surer evidence of soil parentage than the minerals of the clay fraction. The fact that the shapes of particles smaller than one micron cannot be discerned under microscopes depending upon rays of light means that such instruments are almost useless for dealing with clay-size particles. In practice the lower size limit to which mineralogical investigation of soil particles can profitably be carried is usually placed much higher than 1 μ, and workers in this field have found that textbook methods for the handling and identification of mineral grains become increasingly difficult to apply as soon as they come down from average sand-size to very fine sand and silt-size material, i.e. to sizes of *c.* 60 μ–2 μ. The reason for this is that they are concerned not only with seeing the particles, but during the preparative and observational work they are, in fact, testing the physical properties of the minerals and many tests are difficult or impossible to carry out with such small particles. During work on the silt and very fine sand fractions of soils, the writer has found methods of modifying some of the processes of separating, mounting, and testing to make them applicable to these materials. The present account of these methods assumes that the sample has been treated with hydrogen peroxide and any other

reagents found necessary to free the mineral particles and that the clay-size material has been removed.

When the mineral matter of a soil is fractionated for microscopical study the conventional size-classes used in mechanical analysis are inconveniently large, since the diameter of the largest particles in each class is theoretically ten times that of the smallest and the actual size range may be greater still. At best, the mounting of such material without further separation makes the examination tedious and the quality of the image poor, but the most serious trouble is that the combined thickness of the largest particles and the cover glass may be so great that a high-power objective cannot be brought down into focus on the small particles resting on the slide. For this reason in dealing with the separation processes attention will be given to the actual sizes and thicknesses of the particles as distinct from nominal and 'equivalent' diameters, and, in dealing with the mounting, actual thickness of the cover glasses will be discussed together with the 'working distances' of the microscope objectives used in the study of fine materials.

Methods of Separation

Sieve apertures

The sieve used for dividing the fine from the coarse sand should ideally have apertures measuring 200 μ. The nearest British Standard sieves to this value are B.S. 72 (nominally 211 μ) and B.S. 85 (nominally 178 μ). For the latter, which is usually chosen, the maximum apertures tolerated are 228 μ for the 'normal' and 221 μ for the 'special test sieve', the limits which must not be exceeded by 6 per cent. of the apertures being 208 μ ('normal') and 203 μ ('special'). Hence, material passing a B.S. 85 sieve when permanently mounted may well give a thickness of Canada balsam appreciably greater than 200 μ. The separation of the conventional fine sand fraction from silt is attained by sedimentation, but further divisions can be made by using the finest B.S. sieves and so obtaining a 'very fine sand' fraction which will reduce the Canada balsam layer to 70–100 μ (Fig. 1).[1]

One disadvantage of fine wire sieves is that it is almost impossible to free them entirely from trapped particles so that one sample may contaminate subsequent ones. This trouble can be avoided by the use of expendable sieves. Nylon sifting cloths[2] are now available with small and fairly uniform mesh (e.g. sizes listed within the fine sand range are 190, 170, 142, 124, 116, 106, 99, 90, 84, 80, 75, 68, and 61 μ) and the cost of sieves 2 cm. in diameter, which is large enough for micro-samples, is negligible. The threads are somewhat flexible but the material appears to have been treated to prevent them moving out of place. Expendable round-holed sieves may be made by perforating tough paper (e.g. Bristol board) or strong tin foil with a fine needle mounted in a glass tube by means of sealing wax, with the tapered portion of the needle protruding

[1] The British Standards Institution have published data for sieves down to 300 B.S. in British Standard 410:1943 and for the 350 B.S. sieve in Amendment No. 6, 1958.

[2] Obtainable from Henry Simon, Ltd., Cheadle Heath, Stockport.

(Fig. 2*a*). The size of the aperture may be controlled by fitting perforated discs of cardboard of appropriate thickness (Fig. 2*b*).

Expendable sieves of the above-mentioned materials may be cemented to metal cylinders 2 cm. in diameter and about 2 cm. tall, by applying asphalt varnish to one end of the cylinder, allowing it to dry, then warming and pressing it on to the material. When the sieve has been used the cylinder may be detached, cleaned, and used again.

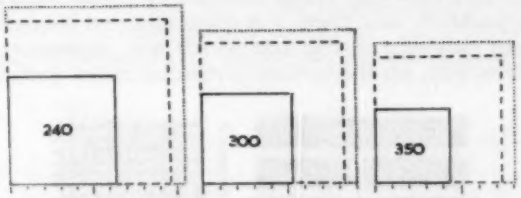

FIG. 1. Tolerance on British Standard Sieves, B.S. 240, 300, and 350. Small squares: nominal mesh size. Large squares: maximum toleration, Normal Standard. Intermediate squares: maximum toleration, Special Standard. Each scale division equals 10 μ.

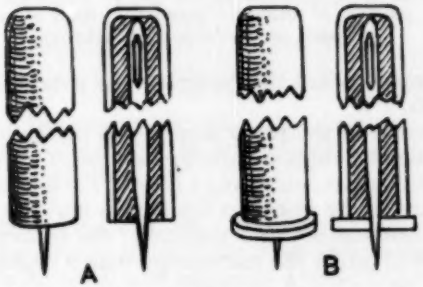

FIG. 2. Mounted needles for perforating foil.

The writer has also devised sieves in which the apertures are slits cut in tin foil and which are suitable for micro-preparations though not for quantitative routine work. These sieves will pass relatively large circular bodies and flakes demanding a Canada balsam layer no greater than the *width* of the slit, which can be made much less than the aperture of a very fine wire sieve (Fig. 3) so that they may be used for separations which on a larger scale would need to be performed by sedimentation methods. For making these sieves two different thicknesses of tin foil have been used and found satisfactory, namely 40 μ and 100 μ.[1] The slits are made with a razor blade while a disc of foil, some 2 cm. in diameter, rests on a glass plate, the width of the slit produced being

[1] Both were of 99·5 per cent. tin; the 40 μ from Vanesta Ltd., Vintry House, Queen Street Place, London, E.C.4, the 100 μ from British Drug Houses Ltd., West Quay Road, Poole, Dorset.

controlled by placing sheets of paper of appropriate thicknesses between the foil and the glass plate. The widths may be checked under the microscope using a micrometer eyepiece and any unduly broad slits may be closed by pressing with the point of a glass rod suitably tapered. For the sake of rigidity, slits should not exceed 1 mm. in length and should be at least 1 mm. apart for otherwise the cutting of one slit may close up the neighbouring one. With practice it is possible to make sieves with slits no wider than 5 μ. When mounting the disc on to the supporting cylinder as already described, it is important that the cylinder should be attached to that side of the disc which was uppermost during the cutting. In this way, on the surface presented to the particles, the slits

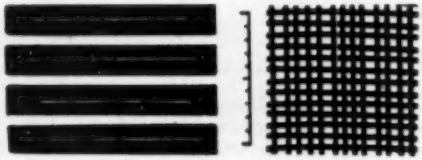

FIG. 3. A, Slit-shaped apertures in tin-foil sieve for silt work. B, B.S. 300 sieve for comparison of size and precision. Each scale division equals 100 μ (photographs).

lie in slight depressions and this facilitates the passage of needle-shaped and platy objects.

Except in the case of the paper sieves, it is preferable to employ wet sieving, using ammonia diluted with distilled water. The sieve should be dipped into a watch-glass containing a little of the liquid and a dispersion of the material should be placed in the sieve a few drops at a time while shaking it both horizontally and vertically, the contents of the watch-glass being checked under the microscope with a medium-power objective.

Sedimentation and panning

The separation of the silt from the fine sand is carried out by sedimentation and the same method with appropriate settling distances and times may be used to subdivide both fractions at any selected *nominal* size limit. In mechanical analysis it is conventionally assumed that the material has a density of 2·65, which is so near to the densities of the limited number of species which usually form the bulk of the mineral fraction that the assumption does not seriously impair the values obtained. In the microscopic study of sedimented fractions, however, the sizes of individual particles become important, since even a few particles with densities lower than 2·65 may mean that some of them will be sufficiently larger than the nominal size as to cause a serious increase in the thickness of the final mount.

If two spheres, of density d_1 and d_2 and diameter D_1 and D_2 respectively, fall with the same limiting velocity in water, density 1, then it

follows from Stokes's Law that $D_2/D_1 = \sqrt{d_1 - 1} \div \sqrt{d_2 - 1}$. If d_1 and D_1 refer to a sphere of standard density, 2·65, then the second sphere, although having a different density and a different diameter, will be given the conventional value D_1. The ratio D_2/D_1 for different values of d_2 are expressed graphically in Fig. 4. Important divergences from unity are shown by opal (present in many soils as phytoliths, diatoms, and sponge spicules),[1] coal fragments (common in drift and soils derived from coal-bearing strata), and the heaviest of the accessory minerals such as zircon, ilmenite, magnetite, and monazite. Where there has been burning of vegetation, soils may contain particles of carbonaceous matter

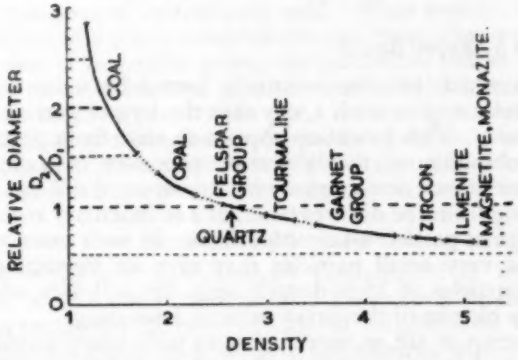

FIG. 4. Diameters of mineral particles, in the 1 to 5 density range, relative to an assumed 'equivalent spherical diameter' of unity.

with densities similar to those of coal. From Fig. 4 one can deduce that, in the fine sand fraction, coal particles with shapes approximating to that of a sphere could show size ranges of 870–87 μ down to 300–30 μ according to their density. For opal the limits would be about 250–25 μ and for magnetite 125–12·5 μ.

Although the above discussion relates to perfect spheres, it suggests that actual sedimentation, either in the laboratory or in nature, will give a material in which the densest mineral particles have, in general, the smallest dimensions, and are thus capable, under appropriate conditions of finding their way through the interstices between the larger particles and becoming concentrated in the lower layers. Thus, if the material is placed in a small, shallow vessel dipping into a larger vessel of water and vibrated by hand for 2 or 3 minutes, a partial separation of this kind occurs, so that if the agitation is increased, the lighter minerals may be washed over the edge of the small vessel into the larger one, just as quartz sand is removed when panning for gold. In this way phyloliths and flaky minerals may be washed from a watch glass into a basin of

[1] Details and bibliographies relating to opaline phytoliths and sponge spicules in soils are given in two recent papers (Smithson, 1958, 1959).

water. The mechanism of panning involves effects of shape, particle-size, and density and in practice the conditions are too complex for mathematical treatment.

It is clear, therefore, that where micro-preparations are concerned both panning and sedimentation must be controlled by methods of trial and inspection.

Since glass vessels can be more thoroughly cleaned than fine wire sieves, sedimentation is preferable where quantities larger than micro-samples are being treated. Small portions of the sedimented fractions may be used for micro-preparations if they are passed through newly made foil sieves to remove any oversize particles.

Separation by heavy liquids

Detritus which has been naturally sorted by water will tend to be already constituted in such a way that the largest particles are those of lowest density. This condition appears to arise from processes resembling a combination of the laboratory processes of sedimentation and panning, and it may occur equally in a transported soil and in a sedentary soil resulting from the disintegration of a sedimentary rock to something like its original particle-size composition. In such cases a sieve separation of the very small particles may give an assemblage sufficiently richer in particles of high density than the soil as a whole to give a satisfactory picture of the heavy mineral assemblage.

The treating of silt or very fine sand with heavy liquids to obtain a heavy mineral fraction uncontaminated by light minerals is beset by many difficulties. Firstly, the condition of the separating liquid may be important, e.g. bromoform gives better results when a little copper gauze, which is said to combine with any free bromine or hydrogen bromide, is kept in the bottle and when a few lumps of fused calcium chloride are kept floating on the surface to absorb moisture. Other causes of imperfect separation and some of the means, such as centrifuging, suggested for dealing with the problem have been discussed by Milner (1940). Jeffries (1941) has described a double centrifuge tube for heavy liquid work in dealing with particles in the range 100 to 50 μ, and Kanno (1958) has published a photomicrograph of a pure separation of soil opal using Thoulet's solution and a Jeffries tube. The author of the latter paper has kindly given me the magnification of this photomicrograph (unfortunately in the paper the word 'micron' is printed where 'mm.' was intended) from which it appears that all the particles are of a size approximating 50 μ. The perfection of the separation is shown by the fact that almost every particle can be identified as a grass phytolith, though to obtain this degree of purity 'it is necessary to centrifuge three times or more'.

A method of assessing the densities of small particles by examining mixed assemblages in heavy liquids under the microscope is described in the section on microscopical examination. Under certain circumstances this method may be used to divide a micro-sample into two density fractions.

Staining Methods

Staining affords some assistance in the recognition of small particles, but as the results depend on the physical condition of the surface and degree of chemical weathering they need to be accepted with caution. Clay minerals and partially altered felspars may be stained by organic dyes without any preliminary treatment. In some cases stained minerals exhibit pleochroism, e.g. dickite (Smithson and Brown, 1957), which provides additional information about the optics of the grain. Hawkins and Graham (1951) have described a method for distinguishing potash and soda-lime felspars in the 5–50 μ fraction by causing the particles to adhere to a slide coated with a film of black rubber cement and subjecting them to a vapour of hydrofluoric acid. When treated, first with a saturated solution of sodium cobaltinitrite, and then, after washing, with a dilute solution of malachite green, the potassium felspar is coloured yellow due to the formation of potassium cobaltinitrite and the soda-lime felspar is coloured blue by the dye. According to Holmes (1921) the most calcic of the plagioclase felspars will become stained with malachite green even if the vapour employed is that of hydrochloric acid, and the felspathoids and certain other minerals also react in this way.

Methods of Mounting

As already explained, one difficulty encountered in work at high magnification is that some particles may lie so deep in the mounting medium as to be beyond the range of focus of the objective. One method of overcoming this difficulty is to have the material mounted between two cover-glasses, these being subsequently protected in a metal or cardboard holder. Ordinary mounts are, however, satisfactory provided that the need for considering cover-glass thickness in relation to particle size, a subject not discussed in standard works on microscopy, is correctly understood.

Cover-glass thickness and working distance

For each objective the manufacturer postulates the nature of the path between the specimen and the objective necessary to obtain an image of good quality. The media traversed by light leaving the specimen (Fig. 5) are the mounting medium, e.g. Canada balsam, b; the cover-glass, g; and a 'working distance' occupied by air (a) in the case of a 'dry' objective or by immersion oil (i) in the case of an oil immersion objective. For a dry objective values for g_s and a_s are specified,[1] e.g. an assumed 'standard cover-glass' has a thickness of $g_s = 180\,\mu$, and for each objective a working distance is given, e.g. for one make of $\times 40$ objective $a_s = 370\,\mu$. No consideration is given to b for the computer assumes that the specimen will always be a thin section in contact with the cover-glass. If the specimen consists of particles of various thicknesses embedded in Canada balsam, which has a refractive index not differing

[1] In the present paper a subscript 's' to a symbol indicates the specified value; symbols without a subscript indicate values which may or may not conform to the manufacturer's specification.

greatly from that of the cover-glass then optimum quality of image will occur when $b+g = 180\,\mu$ (approx.), so that cover-glasses thinner than the standard will give optimum clarity somewhere within the subject and not at the surface of the thickest grains.

Immersion oil has a refractive index nearly equal to that of the cover-glass, so that, with an oil immersion objective, light passing from specimen to objective travels as through a single medium. The manufacturer states a working distance (e.g. $i_s = 120\,\mu$ for a particular $\times 95$ objective) and still assumes $g_s = 180\,\mu$, but so long as the specimen is at a distance $d_s = g_s + i_s$ (in this case $= 300\,\mu$) from the objective it will give a good image. Hence, variations in cover-glass thickness and the presence of a

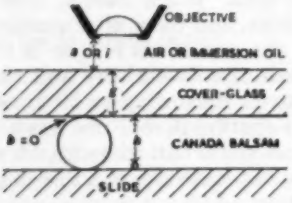

FIG. 5. Measurements relating to problems of cover-glass thickness and working distance of an objective.

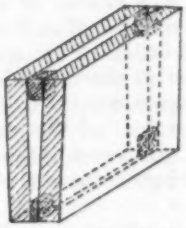

FIG. 6. Device for testing cover-glass thickness.

balsam layer will not impair the image, although if $g+b > d_s$ the specimen will be too low to be brought into focus, even when i is zero (i.e. when the objective mount touches the cover-glass).

From the above examples it follows that if spheres ranging from 20 to $200\,\mu$ are mounted together under a standard cover-glass, then b is $180\,\mu$ for the upper surface of the smallest spheres and since g_s is also $180\,\mu$ the effect with a dry objective is equivalent to using a cover-glass twice the recommended thickness. With the oil immersion objective cited above all spheres smaller than $80\,\mu$ in diameter will be beyond the range of the objective even when racked down to touch the cover-glass. Two courses are open for combating these troubles: (i) to split the sample at a lower limit than $200\,\mu$ by methods already discussed, (ii) to select cover-glasses thinner than $180\,\mu$.

There is no British Standard Specification for cover-glasses and the term 'standard cover-glass' is purely theoretical. In batches measured at this college, No. 0 cover-glasses are normally about 100 to $135\,\mu$ thick, No. 1 about 130 to $185\,\mu$, and No. 2 about 180 to $265\,\mu$, but the finding of a batch of No. 1 cover-glasses ranging from 105 to $260\,\mu$ induced the preparation of a device for checking thickness. This consists of two pieces of microscope slide glass (Fig. 6) separated below by two small pieces of cover-glass selected as having a thickness of $140\,\mu$ measured by an engineer's micrometer, and above by two pieces $240\,\mu$ thick, all held together by glue and the edges strengthened by a binding not shown in the figure. Cover-glasses are inserted at the top and those

which pass through are used for most fine particle work; those which fail to pass are withdrawn and set aside for use when thicker covers are required. If the device is graduated with horizontal lines, the thick glasses may be grouped according to the distance which they are able to penetrate. For example, ten divisions will show increments of 10 μ from 140 to 240 μ.

From considerations set out above, suitability of particle size-limits and cover-glass thicknesses can be assessed for particular cases. For example, if the largest particles passing a B.S. 240 sieve are of a size and shape to keep the cover 100 μ above the slide then for any detail in the mount $b < 100\,\mu$. With the oil immersion objective referred to and a tested cover-glass $b+g+i = d$, becomes $(< 100)+(< 140)+i = 300\,\mu$, making $i > 60\,\mu$, so that when the lowest details are in focus the oil gap will not be less than 60 μ. For the same mount under a dry objective, the most perfect image will be given by details 180 μ below the top of the cover-glass, i.e. at a depth of 40 μ in the balsam, near the mean depth of the material.

Where the particles do not exceed 20 μ, as for example when they have passed a slit sieve, cover-glasses only slightly thinner than the standard value of 180 μ are to be preferred.

Preparation of the mounts

When making mounts of very fine material the slides are cleaned thoroughly (e.g. with a synthetic detergent) and drops of an ammoniated suspension allowed to spread out over the middle of the glass surface. The slides are then warmed, gently at first, to evaporate the liquid without causing flocculation. When moisture and any ammonium salts have been driven off, refractive index liquids or Canada balsam may be added to give temporary or permanent mounts, selecting suitable cover-glasses as discussed in the previous section. By this method the particles, for the most part, remain adhering to the slide in the positions in which they originally settled. To avoid disturbing the particles in making a permanent mount with natural Canada balsam, the balsam should be in a fluid, though viscous condition (made so by warming the bottle if necessary) and the slide should be hot enough to make the balsam flow freely when it touches the slide. Heating should be carried out on a level plate of brass or 'hard-drawn' copper with a bunsen flame applied to one corner so that ranges of temperature are available, and should be continued until a little of the balsam picked up on the point of a needle and cooled in water is found to be only slightly brittle when pressed upon glass. A selected cover-glass is lowered slowly and centred on the slide, which is then drawn over the cooler part of the plate. A piece of glass slightly smaller than the cover-glass is then placed upon it and loaded with a few coins to give a weight of about 40 g., and after a minute or so the slide is transferred to a clean, level surface to cool. The precautions already recommended concerning particle size and cover-glass thickness may be useless unless the cover-glass is properly pressed down.

In some tests the particles need to move in a liquid medium and in this case adhesion to the slide must be avoided. For this reason a part of the

fine material may be dried with gentle heat in a watch-glass to be subsequently dispersed in appropriate liquids. The mounting of dry powders in Canada balsam may cause particles to lie at varying depths, which is always inconvenient, and also to lie in random orientation, which is advantageous only in special cases.

Methods of Microscopical Examination

Assessment of density

It is often useful to examine a silt or very fine sand fraction as a temporary mount in a heavy liquid. If a little dry silt is dispersed as thoroughly as possible in a few drops of the liquid on a microscope slide

FIG. 7. Density separation of mineral grains in a temporary mount.

by stirring with the point of a needle, the gravity separation can actually be observed under the microscope for the heavy and light fractions are found at two different levels of focus, especially when a cover-glass is used resting on two narrow strips of cover-glass (Fig. 7). There are several possible explanations why the separation is more satisfactory under these conditions than in a separating vessel, e.g. the distance of rise is so small that equilibrium is soon obtained, convection currents in the thin film are negligible and the absence of an upper liquid-to-air surface reduces troubles due to surface tension. Until proficiency has been acquired, it is helpful to have parallel ink-lines on the slide coming into focus at the same time as the heavy fraction and a set of lines at right angles to these drawn on the lower surface of the cover-glass near the level of focus of the light fraction. The test is particularly useful for distinguishing minerals with similar optical properties, e.g. calcite (sp. gr. 2·7), aragonite (sp. gr. 2·95), and dolomite (sp. gr. 2·85), or for searching for 'organic silica' (opal, sp. gr. *c.* 2·15, i.e. lighter than almost every other material likely to be present). It is useful to keep a collection of fragments, each a few cubic millimetres in size, of minerals likely to be encountered so that when it is necessary to adjust the specific gravity of a liquid by dilution for separating two minerals, fragments of them will be available as indicators. Tetralin (sp. gr. 0·97) is a suitable diluent for bromoform (sp. gr. 2·85) and for methylene iodide (sp. gr. 3·3) giving mixtures which do not change quickly in specific gravity because of evaporation. If one intends to make a rapid test and recover the heavy liquid it is possible to use benzene as a diluent (for bromoform and for methylene iodide) or ethanol (for bromoform).

On one occasion when this test was employed using pure bromoform, the slide was left overnight and was later found with the light particles adhering to the cover-glass and the heavy ones to the slide, the liquid

having evaporated. Such a micro-separation is not practicable where the liquid is a mixture which changes its density during evaporation.

Examination with the polarizing microscope

The difficulties of studying very small particles under the microscope may be considered as due partly to smallness of area and partly to thinness. A fragment derived originally from a polysynthetic twin of plagioclase may fail to show any twin plane although correctly oriented to do so, if its diameter is less than the width of one component of the twin, and with further diminution of particle size the probability of failure increases. The impossibility of obtaining a recognizable interference figure from a small particle is largely due to the small area which it presents though the shortness of the light path through the particle is also responsible. Shortness of path is also responsible for making some minerals apparently non-pleochroic although their pleochroism is strong enough to be used as a means of identification when dealing with the sand fraction. Little or nothing can be done to combat the above mentioned difficulties.

Thinness of particle may also be responsible for failure to recognize it as feebly birefringent. For dealing with such cases the usual type of compensators (the quarter-wave mica plate, the gypsum plate giving red of the first order, and the quartz wedge giving several orders of Newton's scale) may prove inadequate, and the feebly birefringent mineral may appear isotropic. One method of combating this difficulty is to take the precaution of having a gypsum plate which gives very precisely the 'sensitive tint', i.e. the distinctive purple where red of the first order passes into blue of the second. A small particle of a feebly birefringent mineral tested with this plate will change to bluish violet or a reddish purple according to whether oriented in the additive or subtractive position with respect to the plate. For some physiological reason the eye is particularly sensitive to slight changes at this point on Newton's scale, particularly if the test is made in good daylight. If possible, the gypsum should be mounted between thin cover-glasses in a metal holder, because thicker glass may impair the quality of the image. A useful set of compensators can be made from mica cleaved to give a range of greys including thicknesses less than that of the quarter-wave plate. These cleavage flakes may be fixed to perforated cards cut to fit into the compensator slot of the microscope and should, for maximum clarity, be used without cover-glasses. The several mica plates may be tried in turn to find the optimum for each particular problem. Besides being employed with the usual function of a compensator, they are useful as a means of enhancing contrast (Parry and Smithson, 1958, pp. 547–8), e.g. in recognizing twinning in silt-size microcline or searching a silt sample for plates of dickite. If, for example, the mineral between crossed polars shows a very low (i.e. dark) grey on Newton's scale, a mica plate giving an identical grey can be inserted to change the tone to black or to a grey higher (i.e. lighter) than that of the field, according to orientation.

A few minerals with exceptionally high birefringence are perhaps easier to study when they occur in the silt fraction than when they are

of larger size. For example, when prisms of rutile from the sand and fine sand fractions are seen between crossed polars the observed colour is the sum of a 'high white' on Newton's scale and the natural colour of the grain so that special devices may be necessary to determine the sign of its length. In a silt-size rutile needle, the natural colour is feeble and at a thickness of 2 μ its polarization colour is red of the first order so that determination of elongation presents no difficulty.

Phase-contrast methods

Even with minerals having refractive indices appreciably different from that of the medium, poorness of contrast is a major trouble in the examination of silt size material, and whilst the techniques described above are useful in certain cases, phase-contrast techniques, especially

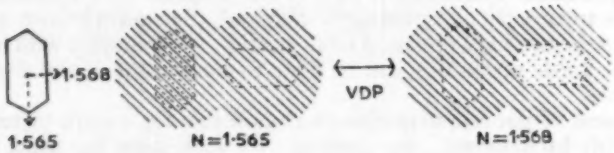

FIG. 8. Refractive index determination by phase-contrast methods. VDP: vibration direction of polar. N: refractive index of medium.

when carried out on an adapted polarizing microscope, are more generally applicable. Some of the principles involved in this work have been dealt with in an earlier paper (Smithson, 1948).

The polarizing phase-contrast microscope is also well suited for determining the refractive indices of small mineral particles by the immersion method, particularly when they are colourless and anisotropic. When working with silt-size material it is not practicable to examine the same particle in a series of liquids and instead one prepares a number of evaporated spreads as described in the section on mounting and adds each liquid to a new slide, protects with a cover-glass and searches for examples of the mineral under investigation. With ordinary apertures in the substage a colourless particle becomes almost invisible when its refractive indices are fairly closely matched by that of the immersion liquid. If, however, a single polar and the sub-stage annulus appropriate to the particular phase-contrast objective are inserted, a birefringent particle which is invisible in one position may be made to contrast with the field by rotating either the polar or (as in Fig. 8) the stage. When the particle is darker than the field in one position and becomes invisible with a rotation of 90°, the refractive index of the medium is lower than one of the refractive indices of the mineral and equal to the other. On the other hand, if the particle is brighter than the field in one position and becomes invisible with a rotation of 90°, the refractive index of the medium is greater than and equal to the two refractive indices of the mineral respectively. A particle of an isotropic mineral (or of one which appears isotropic because it has an optic axis oriented perpendicular to the stage) will be unaffected by the rotation

of the stage, and if perfectly matched with the immersion liquid it will remain quite invisible. Under these circumstances the observer may be uncertain whether he has found the correct immersion fluid or whether the mineral is absent from the fields he has observed. He should then repeat the examination using liquids adjusted to give refractive indices only slightly higher and slightly lower than before and confirm that the mineral now appears faintly whiter than the field in one case and faintly darker in the other.

For rough work, observations may be carried out with white light, and a Leitz Jelley refractometer may be employed for determining the refractive index of the liquid. To obtain more precise values monochromatic light from a sodium lamp may be used in conjunction with an Abbe refractometer.

One useful application of phase-contrast is its use with temporary mounts of a sample in a medium differing in refractive index by about 0·01 from the refractive index of the particular mineral species being studied. For example, 'organic silica' (opal) seen in a suitable water-glycerol mixture of refractive index 1·42 forms conspicuous objects when the mount is being examined with phase-contrast. As a check of identity, the annulus may be momentarily withdrawn and if the material is opal it will practically disappear.

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AN INTERPRETATION OF THE MICRO-MINERALOGY OF CERTAIN GLAMORGAN SOILS: THE INFLUENCE OF ICE AND WIND

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Summary

This investigation shows the complexity of soil materials which will arise in many similar areas due to the combined influence of underlying rock, local ice movement, far-travelled ice, and wind transportation, and its elucidation has been attempted on the basis of a comprehensive knowledge of the mineralogy of the regional soils, geological strata, and superficial deposits. The criteria for recognizing the presence of wind-blown materials (by sorting according to specific gravity) are discussed.

The Dyffryn series is essentially formed on a local drift produced by ice that moved off the Coalfield and traversed the Vale of Glamorgan, this ice also influencing otherwise sedentary soils of the Sand Hall, Cogan, and Worcester series; the Ston Easton series includes soils deriving much of their content from the underlying rock, but some from the Irish Sea Drift and some blown by winds off the coastal sands; and the Gower soils and Sully phase are influenced chiefly by the underlying rock but also by wind-blown material. In some places the Gower series is influenced by the Irish Sea Drift which attains its maximum effect in the Gower Peninsula.

Introduction

SMITHSON (1953) has remarked that the commonly accepted methods of classification of soils into series implies a knowledge of the nature of the contributions to the parent material in which the soil develops. During recent surveying of soils in the County of Glamorgan certain problems relating to the origin of the parent materials arose which, it was considered, could best be resolved by a study of their mineralogy. Consequently, an examination of the mineralogy of the Mesozoic (Crampton, 1960*a*) and Palaeozoic rocks of the region, and the extensive cover of glacial sandy drift (shown as glacial sand and gravel and contemporaneous boulder clay on the Geological Survey sheets 263, 262, and 261) centred on Pendoylan (Crampton, 1960*b*), has already been undertaken. With this basic knowledge seventy soil samples (some from profiles and the remainder from just below the topsoil) have been collected from selected localities in the Vale of Glamorgan and the Gower Peninsula, most of which are recorded on the sketch-map.

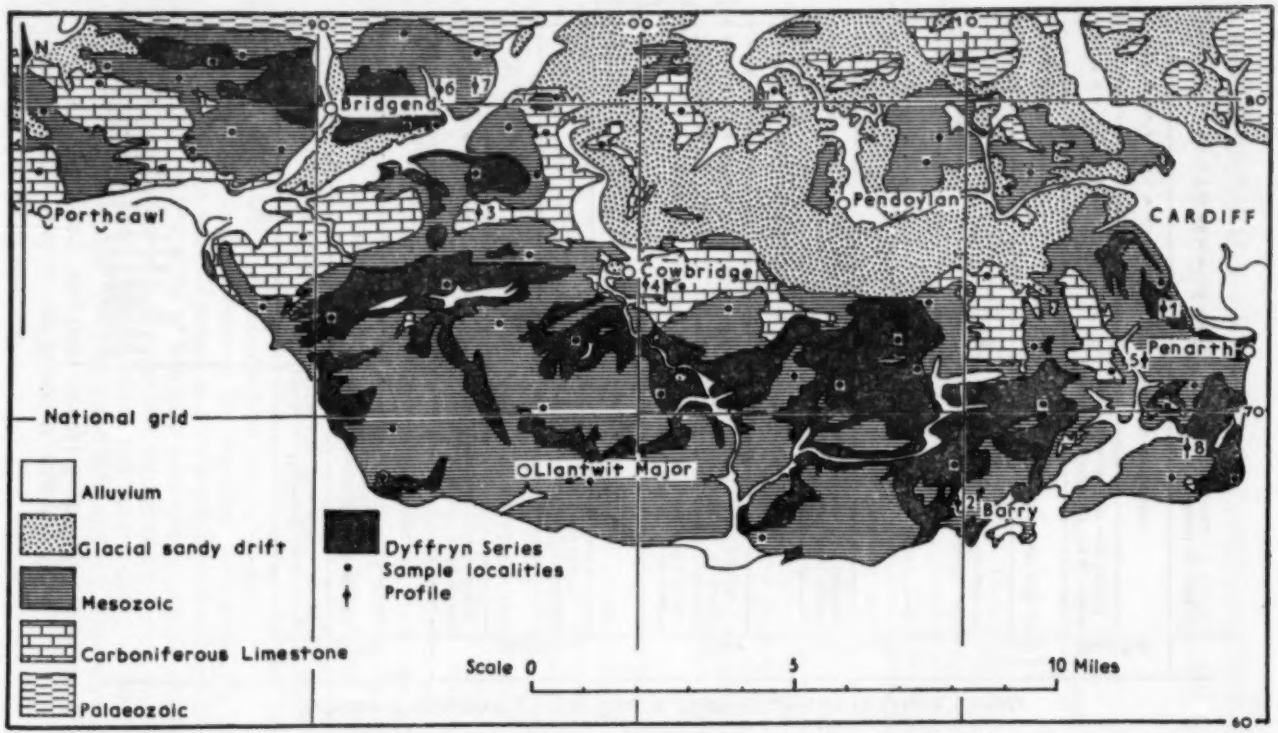
The organic matter was removed by treatment with hydrogen peroxide. The samples were dispersed in a weak solution of sodium hexametaphosphate, and particles of less than 0·02 mm. diameter removed by decantation. The coarser material was separated by sieving through a 60-mesh I.M.M. sieve. Optical study was concentrated on material approximating to fine sand. The heavy and light minerals were separated in bromoform, identified, and their relative proportions determined by microscopic counts of up to 200 grains in each sample.

TABLE 1

Relative Proportions (%) of Heavy Mineral Species in Grain Counts

	Dyffryn		*Ston Easton*			*Gower*		*Sully*		*Cogan and Worcester*		*Sand Hall*		
	Profile 1: Combined grain counts from 1 sample from each horizon.	*Sample 1*: ¼ mile SE. of Kemeg Hill. Grid reference 842822.	Combined grains counts.	*Profile 2*: Combined grain counts from 1 sample from each horizon.	*Sample 2*: Near Lockwith. Grid reference 163744.	*Sample 3*: ¼ mile N. of Merthyr Mawr. Grid reference 886788.	Combined grain counts.	*Profile 3*: Combined grain counts from 1 sample from each horizon.	*Sample 4*: ¼ mile N. of St. Bride's Major. Grid reference 898758.	Combined grain counts.	*Profile 4*: Combined grain counts from 1 sample from each horizon.	*Sample 5*: Near Tythegston. Grid reference 858787.	Combined grain counts.	Combined grain counts for soils of *Cogan series*.	Combined grain counts for soils of *Worcester series*.	*Profile 7*: Combined grain counts from 1 sample from each horizon.	Combined grain counts.	Combined grain counts for soils of *Charlton Bank series*.
Zircon	51	58	60	55	30	42	48	64	50	52	52	58	61	54	56	56	57	63
Garnet	12	9	11	4	3	15	12	6	10	15	22	12	15	17	16	17	14	16
Tourmaline	16	5	9	14	–	9	8	6	5	6	1	3	6	8	8	8	7	3
Rutile	15	14	9	17	7	4	6	16	12	12	13	11	11	9	13	13	12	13
Epidote	8	4	4	4	50	4	4	8	7	3	3	7	2	3	3	2	3	3
Pyroxene	8	0	–	8	0	8	6	0	11	5	2	6	2	2	1	7	3	2
Amphibole	0	0	•	0	0	2	0	–	–	–	2	–	–	1	–	2	–	2
Staurolite	0	3	•	0	–	2	•	0	0	•	1	0	1	–	–	1	•	1
Anatase	0	0	•	0	0	2	•	0	0	0	0	0	0	1	1	0	1	0
Brookite	0	0	•	0	0	1	•	0	0	0	0	0	0	0	0	0	0	0
Sphene	0	–	•	0	0	1	•	0	0	0	0	0	0	0	0	0	0	0
Monazite	–	+	•	0	0	1	•	0	0	0	0	0	0	0	0	0	0	0
Fluorite	–	0	•	0	0	0	•	0	0	0	0	0	0	0	0	0	0	0
Apatite	–	0	•	0	0	0	•	0	0	0	0	0	0	0	0	0	0	0
Topaz	–	0	•	0	0	0	•	0	0	0	0	0	0	0	0	0	0	0
Andalusite	0	0	•	0	0	0	•	0	0	0	0	0	0	0	0	0	0	0
Dumortierite	0	0	•	0	0	0	•	0	0	0	0	0	0	0	0	0	0	0
Vesuvianite	0	0	•	0	3	0	•	0	0	0	0	0	0	0	0	0	0	0
Kyanite	0	0	•	0	0	0	•	0	0	0	0	0	0	0	0	0	0	0
Sillimanite	0	0	•	0	0	0	•	0	0	0	0	0	0	0	0	0	0	0

• Less than 1 per cent.



Sketch-map of part of Glamorgan showing many of the localities from which samples and profiles were collected.

Soils over Lias limestone

(*a*) *The Dyffryn series: the influence of local ice*

The Lower Lias strata outcrop almost continuously in a wide belt adjacent tc the coastline from Penarth to Bridgend. Nowhere are the shales dominant, and the limestones tend to be more massive to the west of the Vale, terminating in conglomerates where they abut against the Carboniferous Limestone. Within an east–west band on the northerly part of the outcrop there is a cover of heavy impeded soil, the Dyffryn series, very different from the lighter, freely drained soils developed on this limestone near the coast. The following profile is typical of the heavier soils.

Profile 1. Dyffryn series

Site: Flat pasture land one mile north-west of Llandough (grid reference 161733), about 260 ft. O.D.

Inches

0–8 Dark grey,* friable, blocky structure, silty clay loam, with weak prismatic structure developing towards base.

8–17 Mottled, brownish-yellow and light grey-blue, silty clay, showing well-developed prismatic structure and abundant manganese concretions.

17–25 Coarsely mottled, yellowish-brown and grey-blue, prismatic structure, labile, silty clay, containing large limestone cobbles of Liassic origin. The structure weakens towards the sharp contact of the profile with the underlying limestone rock.

The heavy mineral assemblage of profile 1 (Table 1) closely resembles that of the underlying rock (Crampton, 1960*a*). The presence of numerous carbonate grains (chiefly dolomite, calcite being more soluble) and quartz euhedra filled with minute vesicles (characteristic of the Mesozoic limestone) also suggests the derivation of much of the content of the profile from the underlying limestone. The presence of limestone cobbles (albeit of Liassic origin), the high proportion of prismatic tourmaline (75 per cent. of the total tourmaline content), and the single grain of hornblende suggest, however, that some material has been derived from elsewhere.

The zircon content of the Lower Lias limestone and shale is 49 and 54 per cent. respectively of the total mineral suite (Crampton, 1960*a*). If grain counts obtained from all samples collected throughout the total extent of these heavy soils are combined (Table 1) there is a noticeable rise in the zircon content to 60 per cent. of the total mineral assemblage.

* Munsell colour names.

(Notes on sketch-map based, in part, on the 1-inch Geological Survey sheets 263, 262, and 261 and, in part, on mapping for the Soil Survey of England and Wales.—'Alluvium' includes river-terrace gravels and dune sand shown on Geological Survey sheets. 'Glacial sandy drift' includes glacial sand and gravel and contemporaneous boulder clay shown on Geological Survey sheets. 'Mesozoic' includes the Lower Lias, Rhaetic, and Trias. 'Palaeozoic' includes Silurian, Old Red Sandstone, and the Carboniferous with the exception of the Carboniferous Limestone which is shown separately for the purposes of the sketch-map. 'Dyffryn Series' shows, in fact, the distribution of impeded soils on Mesozoic rocks, but this is virtually synonymous with the distribution of soils of the Dyffryn series.)

With the exception of epidote there is a compensating drop in the relative proportion of all other mineral species present in both the overlying soil and underlying limestone and subordinate shale. In particular, the proportion of tourmaline in the limestone (17 per cent.) falls to 9 per cent. in the overlying soils, and that of rutile (12 per cent. in the limestone heavy mineral suite and 17 per cent. in the shale suite) to 9 per cent. in the soils. As in certain drift soils on the Magnesian Limestone of Yorkshire (Crampton, 1959), a change in the relative proportions of the heavy mineral species in the drift soils compared with those of the underlying rock implies that some material from outside the outcrop of the underlying limestone rock has contaminated locally derived material.

A very few grains of dumortierite are recorded in the combined grain counts, and its presence in the nearby Rhaetic (Crampton, 1960*a*) suggests the probable source.

Sphene occurs rarely in the Triassic rocks of the Vale (Crampton, 1960*a*), but forms part of a titanium suite (rutile, anatase, brookite, and sphene) characteristic of the Basal Grit of the Millstone Grit (Stuart and Pascoe, referred to by Griffiths, 1939; Simpson, 1932). The heavy mineral assemblage of soil sample 1 contains the complete suite and most probably derived some of its content from the Millstone Grit outcrop a short distance to the north.

One-fifth of all garnets identified and recorded in the combined grain counts are of a red-brown colour and 'hackly' form characteristic of the Millstone Grit (Crampton, 1960*b*), but absent from the Mesozoic rocks of the Vale in which the garnets are colourless or tinged with pink. Red-brown garnets account for 50 per cent. of all garnets present in sample 1, suggesting heavy contamination by material from the Millstone Grit. The spread of this form of garnet, thinly, throughout the full extent of the soils of the Dyffryn series to the Penarth coast suggests that some material from the Millstone Grit has been carried a considerable distance from west to east across the Vale.

Two-thirds of the tourmaline in the soils are prismatic with somewhat rounded rhombohedral terminations, a variety reported by Heard (1922) as most frequently occurring in the Pennant rocks of the South Wales Coalfield. It is suggested that this area might well be one source of the tourmaline, because in the Mesozoic and Millstone Grit strata, and in the glacial sandy drift which has been strongly influenced by the Irish Sea Drift (Crampton, 1960*b*) to the north of the Lias outcrop, the greater part of the tourmaline occurs as rounded flakes.

The broad topography of the Vale of Glamorgan can be considered as consisting of two plateaux, one at a lower level fringing the coast and consisting mainly of the Lias outcrop, and the other at a slightly higher elevation farther inland, the outcrop of the Carboniferous Limestone, covered or strongly influenced in places by the glacial sandy drift, giving rise to the sharp slope running from south-east of Cardiff through Cowbridge and separating the plateaux. During the Pleistocene period extensive ice-floes from distant sources such as Scotland, the Lake District, north-east Ireland, and North Wales piled up within the Irish

Sea and eventually moved southwards around and over the coastal belt of south-west Wales, along the Bristol Channel and adjoining land, including the Gower Peninsula, to the Vale of Glamorgan, overcoming local ice sheets moving south off the Coalfield (Griffiths, 1939; Pringle and George, 1948). The glacial sandy drift has been influenced by both the local ice and the far-travelled ice, the effects of the latter extending right across the Vale of Glamorgan and beyond Cardiff (Crampton, 1960*b*).

During the last resurgence of ice the Irish Sea Ice did not reach beyond south-west Wales. Mineralogical evidence from the soils suggests that local ice-floes moving off the Coalfield entered the Vale west of Bridgend and continued eastwards against the southern edge of the northern plateau, sweeping aside the Irish Sea Drift and spreading Millstone Grit material over the Mesozoic outcrop, in a tract recorded by the present distribution of the Dyffryn series.

To keep the evidence in perspective it must be restated that the heavy mineral assemblage of these soils generally bears a strong resemblance to that of the underlying Lias limestone. The parent material of the soil may be described, essentially, as a local drift.

(*b*) *The Ston Easton series: the influence of far-travelled ice and wind*

In an approximately east–west belt on the southerly outcrop of the Liassic limestones, adjacent to the Glamorgan coastline, lies a cover of lighter, freely drained soils. The following profile is typical of these, and contrasts with profile 1, also on Liassic limestone.

Profile 2. Ston Easton series

Site: Woodland, one mile north-west of Barry (grid reference 096675), 200 ft. O.D.

Inches

0–6 Very dark grey-brown, friable, blocky structure, silty clay loam.

6–12 Yellowish-brown, labile, blocky structure, silty clay loam, containing some small limestone fragments.

The heavy mineral assemblage of profile 2 (Table 1) closely resembles that of the underlying rock, the proportion of tourmaline and rutile suggesting that both limestone and shale have contributed to this profile. The presence of numerous carbonate grains and vesicular euhedral quartz grains also implies that much of the content of the profile has been derived from the Lias rocks. Fifty per cent. of the tourmaline is as prismatic grains (in contrast to rounded flakes in the Mesozoic strata), and these, together with the few grains of pyroxene, suggest slight contamination.

In most samples collected from these soils there is an enriched heavy mineral suite, both regarding quantity and variety of mineral species. This is more characteristic of drift soils and unlike sedentary soils. The combined grain counts (Table 1) reveal the variety of mineral species present, the assemblage being very similar to that of the glacial sandy drift farther north (Crampton, 1960*b*). The zircon content is consequently noticeably lower than that of the heavier soils on the Lias. Although

present in Mesozoic rocks, amphiboles, pyroxenes, kyanite, sphene, and topaz are not present in the underlying limestone and shale. The Rhaetic shales contain hornblende and kyanite; the Triassic limestone, kyanite and sphene, and the marls, topaz. All these minerals are, however, present in these strata as rare constituents, and hence sphene and topaz, together with andalusite, could also have been derived from the Millstone Grit. The minerals sillimanite and vesuvianite can only have been carried to this area by the Irish Sea Ice, and their presence and the enriched heavy mineral suite suggests that many of the mineral species foreign to the underlying Lias strata reflect the influence of the Irish Sea Drift and not neighbouring geological strata. If so, the influence of this drift has been pronounced.

The very different characters of the Dyffryn and Ston Easton series reflect the influences of two different ice movements; the former more local ice movement from the South Wales Coalfield and the latter far-travelled ice movement from the north through the Irish Sea and Bristol Channel.

The assemblage of sample 2 (Table 1), collected under pasture land on a ridge overlooking the Taff estuary, has an exceptionally high pyroxene content, and an unusual assemblage of yellowish-green irregular grains of epidote, colourless and cleaved plates of kyanite, and rounded grains of andalusite, accounting for 12 per cent. of the total suite. The normally abundant minerals, zircon, rutile, garnet, and tourmaline, are much less common than is usual. Nearly all the pyroxene is in the form of prisms of titaniferous augite with jagged irregular terminations. Pyroxene is never as abundant in the Irish Sea Drift (Griffiths, 1939), nor does titaniferous augite account for such a high proportion of the total pyroxene content.

Stuart (1924) has described the heavy mineral assemblage of dune sands blown off the beaches of South Wales. Titaniferous augite is common throughout, and so are kyanite, andalusite, and epidote. Augite (S.G. 3·2–3·6) is one of the lightest heavy minerals and therefore most likely to be carried by wind. Its specific gravity, the location of the site from which the sample was collected, and the particular variety of pyroxene present (titaniferous augite) in the sample and in the shore sands suggest that material has been carried inland from the shore by wind.

Both epidote (S.G. 3·25–3·50) and andalusite (S.G. 3·1–3·2) have low specific gravities for the heavy minerals and could, therefore, be carried by wind in preference to others such as zircon (S.G. 4·5–4·7), rutile (S.G. 4·18–4·25), and the almandite variety of garnet (S.G. 4·1–4·3). It is noticeable that in the assemblage of sample 2 it is chiefly the last three mineral species that have suffered a marked reduction in their fraction of the total assemblage.

Of course, it is to be expected that the light minerals would be carried in far greater quantities by wind. Stuart states, however, that minerals such as quartz have suffered little of the wind abrasion that produces the characteristic form normally associated with wind-blown material. This is not unexpected since the material has been carried for such short

distances. Hence the light minerals are of less value as an index of the extent to which the deposit is wind-borne. Within the prepared mineral samples no definite evidence of wind transportation was discerned in the light fraction.

Kyanite (S.G. 3·6–3·7) would be carried by wind with only moderate ease. Tourmaline (S.G. 2·98–3·20) is almost absent from sample 2, and consequently there should be evidence of its transportation farther inland. Prismatic grains constitute a high proportion of the tourmaline content in both the heavier and lighter soils on the Lias. Because of the virtual absence of this form of tourmaline in the underlying Mesozoic rocks, in considering soils of the Dyffryn series it was suggested that much prismatic tourmaline could be derived from the Pennant rocks of the Coalfield. Equally likely is its derivation, in part, from material blown from the shore and deposited inland. In soils of the Ston Easton series nearer the coastline it is probable that a high proportion of the tourmaline is of aeolian origin.

Like tourmaline, hornblende (S.G. 3·0–3·3) should be carried inland if wind transportation has occurred. Sample 3 (Table 1) was collected under pasture land sloping down to the Ogmore Valley, at the mouth of which is Merthyr Mawr Warren, a large area of dune sand, and contains an unusually high proportion of hornblende in an assemblage including minerals such as vesuvianite indicating the strong influence of the Irish Sea Drift in this soil. In soils developed on the thick cover of sandy drift north of the Lias outcrop, which more completely represents the Irish Sea Drift, the content of hornblende is never high (Crampton, 1960*b*). The average content of amphibole in soils of the Ston Easton series is 6 per cent. (all hornblende). The prevalence of hornblende and pyroxene in wind-blown deposits is recorded by Milner (1952).

Soils over Carboniferous Limestone: the Gower series

The Carboniferous Limestone outcrops around the southern margin of the Coalfield, and an anticlinal fold plunging to the west creates a further series of outcrops from Cowbridge to south-east of Cardiff, the southern limb separating the glacial sands and gravels to the north from the Liassic limestones to the south. The following profile is typical of soils developed on this limestone. Fragments of the underlying rock are distributed throughout the profile.

Profile 3. Gower series

Site: Pasture one mile north-east of Colwinston (grid reference 949768), about 300 ft. O.D.

Inches

0–6 Brown, friable, crumb structure, silty loam.
6–12 Reddish-brown, friable, blocky structure, silty clay loam.

In addition to the heavy minerals recorded in Table 1 for the above profile, the sand was flooded with barite grains, and contained numerous clear quartz euhedra (distinct from those of the Mesozoic rocks), dolomite, and much haematite; an assemblage consistent with the derivation

of the soil entirely from the underlying limestone (Crampton, 1960*b*), except for the presence of a few grains of staurolite which implies slight contamination. Where the limestone circumscribes and merges with the glacial sandy drift centred on Pendoylan the influence of the Irish Sea Drift is, of course, very pronounced. Islands of Carboniferous Limestone in the cover of drift are likewise strongly contaminated. Smithson (1953) describes similar soils in North Wales which, although influenced by the underlying Carboniferous Limestone, are strongly contaminated by the Irish Sea Drift, chiefly sandy material of Triassic origin. In the Vale of Glamorgan, outside this area of influence of the Irish Sea Drift, the samples, with one important exception, collected throughout the length of outcrop revealed very pure assemblages similar to that of profile 3 (Table 1).

Sample 4 (Table 1) of a very shallow, very dark-brown sandy loam, which is probably best correlated with the Marian series of Anglesey (Roberts, 1958), was collected under rough pasture and bracken in the gorge linking St. Bride's Major and Ewenny. The very few grains of andalusite suggests slight contamination by the Irish Sea Drift. The most surprising feature is, however, the unusually high proportion of hornblende and titaniferous augite. These cannot have been derived from the underlying Carboniferous Limestone, but are those heavy minerals of low specific gravity common in blown sand (Stuart, 1924) present on Ogmore Down one mile to the east. The widespread occurrence of these minerals in soils of the Ston Easton series is assumed to indicate the derivation of some of the soil content from the coastal beaches by wind transportation. Hornblende is also particularly widespread in soils on the Carboniferous Limestone, as shown in the combined grain counts (Table 1), and the same process of transportation and deposition is therefore suspected. A similar derivation, in part, for soils on Carboniferous Limestone has been suggested by Findlay (1958) on the basis of mechanical analysis of certain soils of the Mendip Hills.

In the Gower Peninsula the area of soils derived mainly from the underlying Carboniferous Limestone is very limited being confined to the vicinity of the coastline or inland steep slopes, the Gower series being most typically developed around Llanddewi and Oxwich Castle. Frequently the influence of the limestone is reflected in the profile only by a basal horizon of red-brown silty clay loam. Elsewhere in the peninsula the mineralogy of soils on the limestone suggests they are strongly contaminated by the Irish Sea Drift, often to the extent that the limestone ceases to exert any influence.

The shallower profile of the Gower series is probably suitably correlated with the upland phase, and the more extensive, deeper profile, with the lowland phase described by Robinson *et al.* (1930).

Soils derived from Triassic limestones and marls

(*a*) *Sully phase*

The Triassic limestones and calcareous sandstones outcrop predominantly around the margins of the Carboniferous Limestone, and are sometimes conglomerates derived entirely from it. The two largest

outcrops are near Sully (grid reference 152683) and in an arc north of Coity (grid reference 923814). Whereas the Gower series, typically, has a high silt content in the range $50-2\mu$, soils of the Sully phase are usually sandier. Where well developed, as around Sully, it is a very shallow soil, sometimes with rock outcrops, quick to 'burn' in summer. In places, however, it is indistinguishable from the Gower series.

Profile 4. Sully phase

Site: Gently sloping pasture (aspect WNW.) half a mile east of Cowbridge (grid reference 005745), 200 ft. O.D.

Inches

0–3 Reddish-brown, friable, crumb structure, loam, containing conglomerate pebbles.

3–10 Reddish-brown, friable, blocky structure clay-loam.

The heavy mineral species in profile 4 (Table 1) could have been derived from the underlying rock except for amphibole (hornblende) and pyroxene (much of which is augite). An exceptional feature of this assemblage compared with that of the Triassic rock in general is the very low percentage of tourmaline, this implying some contamination. Vesicular euhedral quartz and dolomite are numerous, suggesting a close association of the soil and underlying limestone. This assemblage and that of most others shows a strong uniformity.

As with the similar soils of the Gower series, the presence of amphibole and pyroxene suggests the incorporation of some wind-blown material. The proportion of hornblende rises to 6 per cent., and pyroxene (mostly titaniferous augite with a little aegerine augite) to 7 per cent. in sample 5 (Table 1), collected under undulating pasture land with some rock outcrops, three-quarters of a mile north of the dune sands of Merthyr Mawr Warren. In addition to strong influence of wind-blown material in this sample, reflected as a less pronounced but widespread phenomenon in the combined grain counts (Table 1), the very few grains of vesuvianite present suggest slight influence by the Irish Sea Drift. Like the Gower series, near the area of deep glacial sandy drift around Pendoylan, soils of the Sully phase show pronounced contamination by the drift.

(*b*) *Worcester and Cogan series*

The Triassic marls outcrop chiefly south-west of Cardiff. The predominantly freely drained soils developed are included with the Worcester series if the underlying marl is dominantly red, but with the Cogan series if the soil is strongly influenced by green marls.

Profile 5. Cogan series

Site: Half a mile north-east of Dinas Powis (grid reference 157722), gently sloping (aspect SE.) pasture, 150 ft. O.D. over Trias green marls.

Inches

0–5 Dark grey, hard, blocky structure, clay loam.

5–11 Mottled, dark grey and light green, hard, blocky structure, clay loam.

11+ Poorly laminated, light-green marl.

Profile 6. Worcester series

Site: Half a mile north-west of Coychurch (grid reference 937805), sloping pasture (aspect W.) 150 ft. O.D., over Trias red marls.

Inches

0–4 Dark yellowish-brown, friable, crumb structure, silty loam.
4–10 Brown, friable, blocky structure, silty clay loam.
10–16 Reddish-brown, blocky structure, silty clay loam.
16+ Dark red, poorly laminated, marl.

The relatively high content of garnet in both profiles 5 and 6 (Table 1) compared with the extremely low content in the underlying marl (1 per cent.) implies some contamination. There is a compensating fall in the proportion of zircon compared with that of the underlying rock (73 per cent.). Material carried from surrounding Mesozoic strata by local ice would raise the proportion of garnet in this striking fashion and depress the proportion of zircon. Nearly one-third of the garnet in soils of both series is of the red variety, the nearest rich source being the Millstone Grit. The ice-floes from the Coalfield, assumed to have distributed this variety throughout soils of the Dyffryn series across the Vale, apparently also deposited material of Millstone Grit origin on outcrops of Triassic marl. The small quantity of yellow garnet present in soils of the Cogan, Worcester, and Dyffryn series could have been carried by the same ice from outcrops of the Carboniferous Limestone (Crampton, 1960*b*).

The small amounts of hornblende and augite present in these soils, and possibly a high proportion of the prismatic tourmaline, can be explained as wind-blown material incorporated with material derived largely from the underlying rock, but with some local drift.

Soils derived from Rhaetic sandstone and shale; the Sand Hall and Charlton Bank series

The Rhaetic shales (with subordinate limestone) outcrop to the west as a thin band around the perimeter of the Liassic limestone outcrop. In depressions the overlying soil can be very deep, but ascending the Lias escarpment it becomes shallower and grades into soils of the Dyffryn series.

The Mesozoic sea had its margin to the north-west (Pringle and George, 1948), and sandstone of the littoral zone first appears near Cowbridge and gradually dominates the lithology of Rhaetic strata towards the north-west. Shallow sandy soils occur where massive sandstone forms prominent ridges, as on St. Mary Down (grid reference 963794), but more often limestones and shales are intercalated with the sandstones yielding brown to yellow-brown silty loams 2 to 3 ft. thick.

Profile 7. Sand Hall series

Site: One mile north-east of Coychurch (grid reference 947809), gently sloping pasture (aspect WSW.), 300 ft. O.D., over Rhaetic sandstone.

Inches

0–3 Dark yellowish-brown, friable, crumb structure, sandy loam.
3–17 Dark brown, friable, sandy loam, containing many sandstone fragments.

Profile 8. Charlton Bank series

Site: One-third of a mile north-east of Cog (grid reference 168690), pasture at the crest of a ridge 75 ft. O.D., over Rhaetic shales.

Inches

0–8 Dark grey, hard, blocky structure, silty clay loam.

8–16 Mottled, blue-grey and brownish-yellow, intractable silty clay, strongly developed prismatic structure. Numerous manganese concretions present.

16–30 Mottled, dark grey and light olive brown, labile, silty clay, weaker prismatic structure, development of lamination in depth as profile grades into shale.

These soils are predominantly sedentary, although the lower proportion of tourmaline and rutile in the mineral assemblage of profile 7 (Table 1) compared with that of the underlying rock (20 and 12 per cent. respectively) suggests general contamination, and the high proportion of hornblende and prismatic tourmaline (43 per cent. of total tourmaline content) in particular, the incorporation of some wind-blown material.

The mineral assemblage of some of the samples from soils over Rhaetic sandstone are characteristic of the suites of nearby rock outcrops of different stratigraphical age. In a sample collected two miles ESE. of Cowbridge (grid reference 026736) under flat pasture south of an extensive outcrop of Carboniferous Limestone, there is abundant haematite, dolomite, and clear quartz euhedra, suggesting that much soil material has been derived from Carboniferous Limestone. However, the parent material, the Rhaetic littoral sandstone deposit, was also formed by a very local detritus (Crampton, 1960*a*). Hence the abundance of minerals characteristic of the Carboniferous Limestone may originate from the limestone indirectly through the Rhaetic sandstone. The presence of brookite and some red garnet in this sample does, however, suggest that some of the soil has been derived from further travelled Millstone Grit.

This interpretation is supported by the evidence from samples collected south of Cefn Cribwr, north-west of Bridgend. Here, again, the mineral assemblages of soil and underlying Rhaetic sandstone suggest a very local derivation of material from the adjacent Millstone Grit. Considerable quantities of Millstone Grit erratics, however, are scattered over the outcrop of Mesozoic rocks between Bridgend and Pyle, and now form an integral part of the soil. Thus the soil must have derived some of its content directly from the Millstone Grit as well as indirectly through the underlying Rhaetic sandstone.

The mineral assemblage of samples collected from the Charlton Bank series indicates the virtually dominant influence of the underlying Rhaetic shale.

Conclusions

The Dyffryn series is essentially derived from a local drift, the distribution of which records the passage of ice moving off the Coalfield and east across the Vale of Glamorgan over Lias limestones and against the southern edge of the northern plateau late in the glacial history of

this region. Although predominantly sedentary in character, soils of the Cogan, Worcester, and Sand Hall series also reflect the passage of this local ice. Soils of the Ston Easton series in an east–west belt adjacent to the coastline have been influenced by the Irish Sea Drift which traversed the region earlier in the glacial history. Despite this contamination, the underlying Lias limestone has exerted a strong influence on these soils and they remain similar to soils of the Ston Easton series as mapped in Somerset. Except in the vicinity of the glacial sandy drift around Pendoylan, the effect of glacial drift is small. Soils of the Gower series are largely derived from the Carboniferous Limestone, although the influence of the Irish Sea Drift reaches a maximum in the Gower Peninsula.

Throughout the Vale there appears to have been a considerable influx of the lighter of the heavy minerals such as tourmaline (prismatic), amphibole, and pyroxene. In the absence of any conclusive evidence based on the light minerals, this is interpreted as indicating aeolian deposition of material carried from the coastal shore sands. The effect is most marked in the Ston Easton and Gower series, particularly regarding unusual concentrations of amphibole and pyroxene at sites near the coast. The effect extends inland and, to some extent, has influenced most of the soils described, including those of the Sully phase and Sand Hall series, the former, together with the Gower series, being otherwise mostly derived from the underlying limestone. Acting since Pleistocene times this process would have caused considerable contamination of local material.

The complexity of soil material arises from the combined influence of underlying rock, local ice movement, far-travelled ice, and wind transportation, and its elucidation is possible only with a comprehensive knowledge of the mineralogy of the regional soils, geological strata, and superficial deposits.

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DEFINING THE STATE OF REDUCTION OF A PADDY SOIL

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Summary

The empirical terms 'oxidizing conditions', 'healthy reducing conditions', and 'extreme reducing conditions' as they are applied to paddy soils are discussed. The expression $r_{E_h} = E_h + 0{\cdot}180$ pH is used to define these conditions more precisely, on the assumption that the presence of ferrous and ferric iron is necessary for healthy reducing conditions for rice. The concept may be useful in both well-established and newly developing rice-growing areas.

MUCH evidence has now accumulated on the changes taking place in waterlogged paddy soils, including observations on the E_h and pH changes (de Gee, 1950; Iri *et al.*, 1957; Tomlinson, 1957; Yu and Li, 1956), the increase in available phosphate (Gasser, 1956; Shapiro, 1958), the nitrogen losses, the increase in available nitrogen and the need for its careful placement because of the reducing conditions (Abichandi and Patnaik, 1958; Mikkelsen and Finfrock, 1957; Mitsui, 1955), the appearance of compounds toxic to rice (Lockard and McWalter, 1956; Ponnamperuma *et al.*, 1955; Ponnamperuma, 1955), and on the rice diseases partly or wholly due to the extreme reducing conditions (Vámos, 1959). The last two points have received especial attention in Japan where, through high sulphur levels in the soil and extreme reducing conditions, the disease 'Akiochi' causes yield losses on degraded paddy soils (Mitsui, 1955; Yamaguchi *et al.*, 1958).

It has been shown that the rice roots are able to function in the reducing conditions because the plant furnishes them with a protective film of oxygen (Alberda, 1953; Yamada and Ota, 1958; Yamaguchi *et al.*, 1958).

It is probably correct to say that at optimum conditions the higher yields from lowland rice, often being maintained without the need for added fertilizers, are in great part due to the low soil E_h giving high levels of easily available phosphorous and available nitrogen and that the rice plant does not suffer from the low E_h because it can protect its roots from the reduced bulk soil. Conditions will be less than optimum when nitrogen escapes as gas, when phosphorous and nitrogen become less available, when toxic compounds—especially H_2S—appear and when the concentration of reduced substances becomes too high for the oxygen-containing rhizosphere to cope with them.

There thus become empirically defined, 'oxidizing conditions'—those of a normal aerated soil, 'healthy reducing conditions'—in which the rice plant can flourish, much nitrogen and phosphorous being available, and 'extreme reducing conditions'—in which the rice plant cannot flourish, the rhizosphere being unable to protect the roots. The need to establish healthy reducing conditions is instanced by work on the desirability of either draining the fields or of adding extra organic matter to them

(Basak *et al.*, 1957; Desai and Seshagiri, 1957; Ghose *et al.*, 1956) presumably depending on the conditions being too reducing or too oxidizing respectively.

From experiments on English soil the author (Jeffery, 1960) has put forward, for waterlogged soils containing active organic matter, ferrous iron in solution and solid ferric hydroxide, the tentative equation:

$$E_h = 1{\cdot}060 - 0{\cdot}0585 \log a_{Fe^{++}} - 0{\cdot}175 \text{ pH at } 22°. \quad (1)$$

This may be rewritten, taking $-\log f_{Fe^{++}} = 0{\cdot}25$ as in the previous paper:

$$E_h = 1{\cdot}033 - 0{\cdot}0601 \log c_{Fe^{++}} - 0{\cdot}180 \text{ pH at } 30°. \quad (2)$$

The applicability of this equation has been tested by evaluating separately:

$$r_h = E_h + 0{\cdot}180 \text{ pH} \quad \text{(at } 30°\text{)} \quad (3)$$

$$r_{Fe} = 1{\cdot}033 - 0{\cdot}0601 \log c_{Fe^{++}} \quad \text{(at } 30°\text{)} \quad (4)$$

If equation (2) is applicable, then r_{E_h} should equal r_{Fe}. The temperature coefficients of r_{E_h} and r_{Fe} can be estimated as approximately $-0{\cdot}004$ volt deg.$^{-1}$ by taking $c_{Fe^{++}} = 10^{-3}$.

Five Sierra Leone paddy soils have been examined by methods similar to those used in the last paper and equation (2) used to show how, if it is correct, the terms 'oxidizing conditions', 'healthy reducing conditions', and 'extreme reducing conditions' may be more precisely defined.

Materials and Methods

Soils

Number	*Site*	*Description*	*Yield lb./acre*	Fe *content by* HCl *digestion g.* Fe/100 *g.*	*Organic matter g.* C/100 *g.*
I	Rokupr farm	Tidal mangrove swamp	3,000	3·6	3·5
II	Rokupr farm	Acid mangrove swamp, often useless for rice	Often fails	3·2	3·6
III	Mando	Fresh water seasonal swamp	1,700	2·5	..
IV	Mando	Fresh water deep flooding seasonal swamp	+1,700	2·5	2·1
V	Kontobi	Inland flood plain, erratic deep flooding, often poor yields	650	0·36	1·9

Yield data, provided by A. J. Carpenter, Botany Department, W.A.R.R.S., are based on small plot trials.

The soils were air-dried and ground to pass a 2-mm. sieve.

Organic matter

Rice straw from Rokupr was chopped small with scissors, rice roots from Rokupr farm, dug from ground, were chopped small with scissors after being washed free from soil.

Ferrous iron in the soil solution

12-g. samples of soil were submerged under nitrogen in 50 ml. of water. Aliquots of the soil solution were pipetted direct into α,α′ dipyridyl, centrifuged, and the colour determined.

Ferrous iron extracted by NH_4Cl–HCl

After the ferrous iron in the soil solution had been determined, the entire sample was extracted and the ferrous iron content determined by α,α′ dipyridyl. The author hopes to publish later a full description of these iron extractions.

Separate duplicate experiments were set up for these iron determinations to be made after 0, 2, 4, 7, 14, 21, and 28 days' submergence.

E_h *and* pH

Performed as before (Jeffery, 1960) on samples of 60 g. soil plus 250 ml. of water which were kept stored under nitrogen. Some of these were set up in duplicate, the agreement was satisfactory.

All the samples were stored in the laboratory at a fairly constant temperature of 30° C.

Results

Fig. 1 illustrates the results. The E_h and pH curves are very similar to those of the previous paper, there is, however, no period 'A' of intense reduction, the straw and roots giving E_h/time curves more like those of the grass after aeration. Where there is a positive slope for the plot of ferrous iron extracted against time, as for the first 21 days of this example, the author argues that it is reasonable to assume there is still ferric iron remaining to poise the solution according to equation (2). As can be seen from the plots, the determinations of ferrous iron in the soil solution were not entirely satisfactory, some was possibly lost by oxidation.

Table 1 gives the data for the five soils with and without additions. The results for 'soil+Fe_2O_3' were closely similar to those for 'soil only' and are not given. Also the results for soil IV were very similar to those for soil III and are not given. E_h and pH readings were taken daily, the values given being taken from the curves drawn through the plots. The ferrous iron values are the means of duplicated determinations. For the ferric iron remaining column, O = no ferric iron remaining, + = ferric iron remaining, this was assessed in each case from the ferrous iron extracted plots, as described above. Equation (3) was used to determine r_{E_h} and equation (4) to determine r_{Fe}.

There is some measure of agreement between r_{Fe} and r_{E_h}. It is encouraging to note that for 'soil V only', from a site where the rice shows phosphate deficiencies, the r_{E_h} values fall in the 'oxidized' range (see discussion) and, as would be expected, $c_{Fe^{II}}$ is very small, whilst soil II from a site where rice growth can be troubled by severe toxicities—attributed by Tomlinson, at least in part, to iron r_{E_h} falls in the 'extremely reduced' range and r_{Fe} is too large, as would be expected if all the iron present has been reduced to the ferrous form. The curves for

iron extracted with time agree with this. Soils III and IV, however, grow fairly good rice though r_{E_h} is rather high and $c_{Fe^{II}}$ less than 10^{-4}, the method of determining $c_{Fe^{II}}$ was not altogether satisfactory and the small amounts of iron here may have become oxidized.

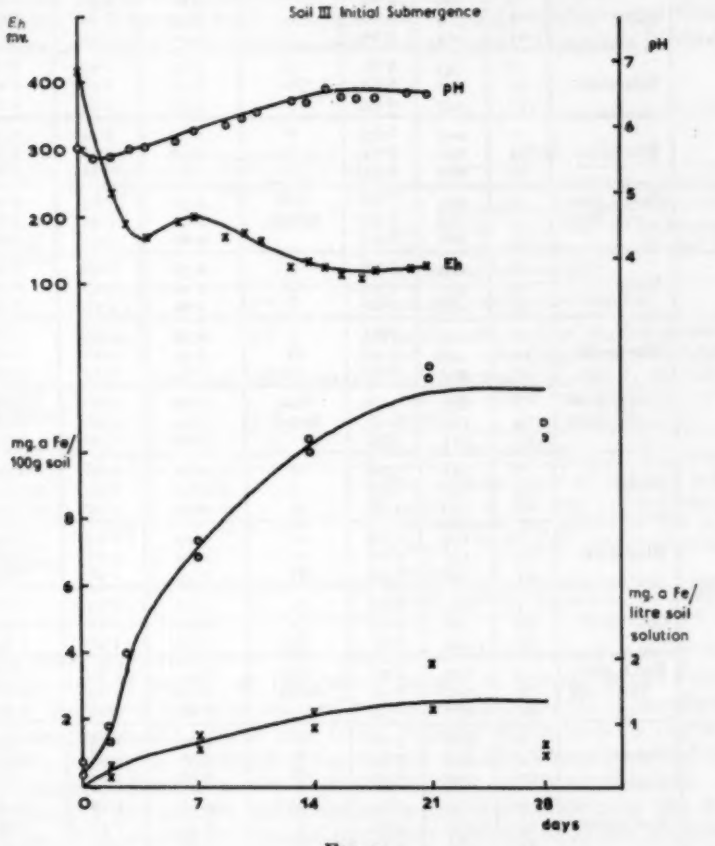

FIG. 1

Discussion

There is a great deal of evidence that rice grows best when iron is present in both the ferrous and the ferric states. Most of the work on Akiochi soils shows the need for free ferric iron (see Mitsui, 1955, for general description) and nearly all papers giving soil solution analyses show quantities of ferrous iron. The figures of Clark and Resnicky (1956) and of Ponnamperuma are of the same magnitude as the author's. Where the slope of ferrous iron extracted/time is positive the author takes it as evidence that there is still ferric iron present and thus r_{E_h}

TABLE 1

Soils	*Additions*	*Days subm.*	E_h *mV.*	pH	Fe^{III} *remaining*	$c_{Fe^{II}}$ *m. e./l.*	r_{E_h}	r_{Fe}
I	None	7	360	4·88	+	0·01	1·24	1·33
		14	320	5·10	+	0·43	1·24	1·24
		21	205	5·80	+	0·71	1·25	1·22
	Rice straw	7	045	6·60	+	3·05	1·24	1·18
		14	020	6·68	+	2·36	1·22	1·19
		21	025	6·74	+	3·37	1·24	1·18
	Rice roots	7	040	6·65	+	1·97	1·24	1·19
		14	001	6·74	+	2·51	1·22	1·18
		21	005	6·74	+	3·21	1·22	1·28
	Fe_2O_3 plus rice roots	7	025	6·66	Not detnd.	0·56	1·23	1·23
		14	005	6·90		1·61	1·25	1·20
		21	000	6·90		2·86	1·24	1·19
II	None	7	220	4·20	+	6·36	0·98	1·16
		14	260	4·50	O	3·90	1·07	1·17
		21	275	4·60	O	3·09	1·10	1·18
	Rice straw	7	125	5·00	+	6·36	1·03	1·16
		14	100	5·90	O	3·34	1·16	1·18
		21	095	6·05	O	1·00	1·19	1·21
	Fe_2O_3 plus rice straw	7	290	3·93	Not detnd.	1·00	1·00	1·21
		14	255	4·47		3·94	1·06	1·18
		21	215	4·90		4·66	1·10	1·17
III	None	7	340	5·08	+	< 0·01	1·26	> 1·33
		14	351	5·00	+	< 0·01	1·25	> 1·33
		21	435	4·82	+	< 0·01	1·30	> 1·33
	Rice straw	7	193	5·70	+	0·49	1·22	1·23
		14	130	6·28	+	0·69	1·26	1·22
		21	110	6·40	O	1·34	1·26	1·20
	Rice roots	7	123	6·20	+	4·27	1·24	1·17
		14	100	6·53	+	0·49	1·28	1·23
		21	102	6·45	O	0·50	1·26	1·23
	Fe_2O_3 plus rice roots	7	110	6·25	Not detnd.	0·29	1·34	1·24
		14	090	6·45		0·79	1·25	1·27
		21	073	6·53		1·00	1·25	1·21
V	None	7	374	5·32	+	< 0·01	1·33	> 1·33
		14	346	5·20	+	0·08	1·28	1·28
		21	320	5·30	O	0·06	1·28	1·29
	Rice straw	7	255	5·10	+	0·31	1·18	1·24
		14	290	4·90	+	0·43	1·17	1·23
		21	285	5·10	O	0·35	1·21	1·24
	Rice roots	7	225	5·45	+	0·90	1·21	1·21
		14	230	5·26	+	0·90	1·18	1·21
		21	125	6·40	O	0·88	1·28	1·21
	Fe_2O_3 plus rice roots	7	065	6·61	Not detnd.	0·47	1·26	1·23
		14	052	6·67		1·65	1·25	1·20
		21	038	6·75		1·07	1·25	1·21

should equal r_{Fe}, when the curve flattens out, slope zero, then he assumes that all the iron has been reduced and r_{E_h} should be less than r_{Fe}.

The controversy as to whether ferrous iron and other reduced substances are toxic to rice (Ponnamperuma *et al.*, 1955; Lockard and McWalter, 1956) or no (Ponnamperuma, 1955; De and Mandal, 1957) is significant. Iron will form complexes of varying stability—and thus of varying resistance to oxidation—with the organic compounds formed

TABLE 2

State of oxidation	r_{Eh}	Fe^{++} *concentration*	*Soil*
Oxidizing conditions	> 1·34	all as Fe^{III}	State of a normal aerated soil and of the rice rhizosphere, the advantages of a previously reducing environment either lost or being lost, N and P becoming less available.
	1·34	10^{-5}	Iron starts going into solution.
Healthy reducing conditions	1·27	10^{-4}	The rice plant enjoys the full benefits of the waterlogged environment, much available N and P, the roots can be safely protected by the plant.
		Fe^{II} and Fe^{III} present	
	1·21	10^{-3}	
	1·15	10^{-2}	Perhaps iron toxicity.
Extreme reducing conditions	< 1·15	all as Fe^{II}	The concentration of reduced substances in the soil solution liable to become too great for the rice roots, H_2S and other toxicities occur.
	1·01	..	Much sulphide formation probable.

under anaerobic conditions. The oxidation of these compounds by the rhizosphere will depend on the rate of supply of oxygen to the rhizosphere, the rate of travel of reduced substances through the rhizosphere, the concentrations of these and other reduced substances in the soil solution, the ease of oxidation of the organic radicles themselves, and the concentration of ferrous iron with which they are in equilibrium. If equation (2) defines the oxidation-reduction system poising the soil solution, then, as soon as it comes in contact with the oxygen-containing rhizosphere, iron will precipitate and the complexes will be liable for destruction. If r_{E_h} is lower than r_{Fe} a greater quantity of oxygen will be required to protect the roots from soluble iron. The same type of argument can be advanced for the effects of other reduced compounds.

For severe iron toxicity the figures of Ponnamperuma give $c_{Fe} = 10^{-3}$ approximately and thus $r_{Fe} = 1{\cdot}12$. Butlin (1956), for the proliferation of sulphide bacteria, gives an E_h of -250 mV. at pH 7 and thus $r_{E_h} = 1{\cdot}01$. Table 2 has been compiled using these figures and assuming for optimum growth of rice $c_{Fe^{++}} = 10^{-3}$ to 10^{-4} (see Jeffery, 1960).

If the concept advanced in Table 2 is correct and assuming that conditions in laboratory samples can be applied or adjusted to field conditions,

it should be useful from several points of view in practical rice farming, such as:

(*a*) where water is limited, under controlled irrigation, for assessing the optimum depth and duration of flooding;
(*b*) in areas not amenable to controlled irrigation, for examining the possibilities of improving soil conditions by adding iron-rich material—if they are too reducing, or organic material—if they are too oxidizing;
(*c*) in areas with high sulphur levels, for testing the likelihood of Akiochi occurrence;
(*d*) in newly developing areas, for examining the suitability of the soil for rice farming.

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INFLUENCE OF SOIL-WATER SUCTION ON SOME MECHANICAL PROPERTIES OF SOILS

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Summary

The experiments described, using kaolinite, were designed to prove the theory that for a *saturated* soil internal soil-water suction is quantitatively equivalent to an externally applied all-round mechanical pressure.

Introduction

ALTHOUGH soils are usually regarded in agriculture as an environment for plants, they also serve as media for bearing vehicles, stock, and man. Failure of land to support such loads makes it difficult or impossible to carry out tillage operations, for example. From common experience, these difficulties are encountered when the soil is wet, and drainage systems are often installed to help alleviate this condition. The design of drainage systems to bring about a given lowering of water-table levels is in an advanced state of development (see, for example, Luthin, 1957); but the information required for deciding at what depths the water-tables should be situated is lacking. It is therefore relevant to study how the wetness of the soil influences the bearing capacity, since this is one aspect in the need for field drainage.

When a static load rests on soil it will sink in through soil failure if the pressure applied to the soil is greater than the bearing capacity of the soil. The bearing capacity depends on the shear strength of the soil (see further). Increase in the compressive forces acting on a soil element leads to an increase in the shear strength. Theoretical considerations lead one to suppose that soil-water suction induces such compressive forces: the experimental confirmation of this forms the subject of this paper. An increase in soil-water suction at all points in soil above a water-table is one consequence of lowering the water-table by field drainage.

Theory

Soil mechanics

In order to be able to follow the later parts of this paper, it will be necessary to give a brief outline of some concepts of soil mechanics.

Consider a rectangular block of material $ABCD$ and let normal and tangential forces be applied to the upper half so that there is a uniform normal stress N and a uniform shear stress F over some plane XY (Fig. 1). With N maintained at some value it is found that the material will fail along the plane XY when F attains a certain limiting value. Moreover, for every value of N, there is a corresponding value for F. Coulomb (1776) showed that this relationship could be expressed by a linear equation

$$F = c + N\tan\phi. \qquad (1)$$

c is usually referred to in engineering literature as the cohesion and is simply the intercept on the F axis. ϕ is known as the angle of shearing resistance (or angle of internal friction in the older texts) and is the slope of the so-called Coulomb failure line (Fig. 2).

Let us now consider the mechanical equilibrium of a vertical cylinder of soil under the action of a lateral stress σ_{111} and a vertical stress σ_1 (Fig. 3).

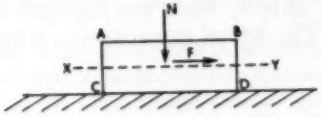

FIG. 1

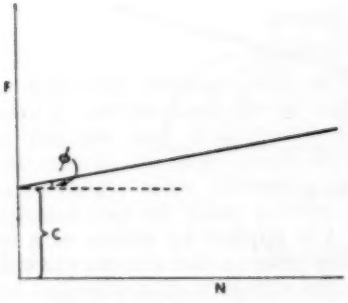

FIG. 2

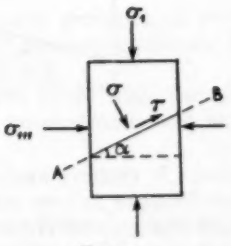

FIG. 3

The normal and tangential stresses σ and τ respectively across any given plane can be expressed in terms of σ_1 and σ_{111} by the equations

$$\sigma = \sigma_1 \cos^2\alpha + \sigma_{111} \sin^2\alpha, \tag{2}$$

$$\tau = \frac{\sigma_1 - \sigma_{111}}{2} \sin 2\alpha, \tag{3}$$

where α is the angle made by the plane and the direction of the stress σ_{111} (see any standard text, e.g. Taylor, 1948).

If the stress σ_1 is increased, a limiting value will be attained when the cylinder fails across some such plane as AB. The value of τ and σ across that plane must then satisfy Coulomb's equation (1) with τ replacing F and σ replacing N. Further, the failure plane can be shown to be that defined by

$$\alpha = \frac{\pi}{4} + \frac{\phi}{2}. \tag{4}$$

A series of different values for σ_{111} will give rise to a series of values for σ_1 at failure from which values for N and the corresponding values of F can be determined. This forms the basis of the triaxial compression test used in soil mechanics.

It should be noted that it is not necessary to perform the calculations of equations (2), (3), and (4) in order to obtain the Coulomb failure line,

since this can be found by a simple graphical method, widely used in soil mechanics, due to Mohr (Fig. 4).

The values of σ_1 and σ_{111} are marked off along the N axis and a circle is drawn with its centre on the N axis and its circumference passing through σ_1 and σ_{111}. The Coulomb failure line is the envelope to all such circles.

In the practical test apparatus, the cylindrical sample is usually enclosed in a rubber sheath, while the top and bottom are closed by plates (see further). The lateral pressure σ_{111} is applied by a fluid such

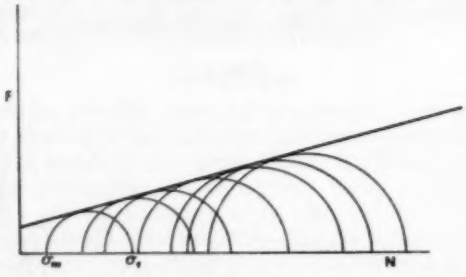

FIG. 4

as water. A vertical load $(\sigma_1-\sigma_{111})$ is applied by means of a loaded plunger brought to bear upon the top plate so that the net vertical load is σ_1 (see Bishop and Henkel, 1957, for complete discussion).

The lower plate is often porous to allow drainage when required. This gives rise to various types of tests depending on whether drainage is permitted during the application of the lateral loading, during the application of all loads, or not at all. For a given soil, there will be a different Coulomb failure line corresponding to each of these tests.

From equations (1), (2), (3), and (4) we can derive an expression for the limiting value T of σ_1 at failure, viz.

$$T=\frac{2c\cos\phi}{1-\sin\phi}+\frac{1+\sin\phi}{1-\sin\phi}\sigma_{111}. \qquad (5)$$

In words, this shows how for a given soil under a given condition of drainage, the crushing strength T increases with the lateral restraint σ_{111} applied to the soil.

Hypothesis on the quantitative equivalence of soil-water suction and an externally applied isotropic pressure

Childs (1955) demonstrated the quantitative equivalence of soil-water suction and an externally applied isotropic pressure in strengthening sand.

Consider a cylindrical sample of a saturated soil set up in a triaxial compression apparatus with drainage permitted to free water. Suppose that it has come to equilibrium under the action of an all-round pressure σ_{111} (i.e. without the loading plunger acting).

Let us now imagine that (1) we replace the water that transmits the pressure to the sample by compressed air at the same pressure, and (2) we remove the rubber sheath. Provided the ambient pressure is below the air entry value for the soil, the sample is apparently in the same mechanical equilibrium as before. The air-water interfaces at the surface serve as the barrier originally provided by the rubber sheath. But we now have the familiar pressure plate apparatus in which the applied pneumatic pressure is identified with the soil-water suction of the soil sample.

We are therefore led to conclude that a saturated sample experiences an all-round pressure equal in magnitude to the soil-water suction. The crushing strength T of an unconfined sample (i.e. no external lateral pressure applied) is then given by equation (5) with σ_{111} replaced by the suction s, so that we obtain

$$T = \frac{2c\cos\phi}{1-\sin\phi} + \frac{2\sin\phi}{1-\sin\phi}s. \qquad (6)$$

(N.B. Since the suction s acts as an all-round pressure, it must be included in the left-hand side of equation (5) in order to obtain T, the actual load that must be applied to cause failure.)

It should be specially noted that we have dealt with the case of *saturated* media only. Extension into the unsaturated case is more complicated and still being studied.

Experimental

The experiments to test this hypothesis consisted in bringing small bricks of kaolinite into equilibrium with different suctions in pressure-membrane apparatus. At each value of suction a simple unconfined compression test was carried out on them. The Coulomb failure line was determined assuming the equivalence postulated above. Standard engineering consolidated undrained triaxial compression tests were performed using the same clay. The Coulomb failure was found in the usual way, and compared with the other.

The unconfined compression tests

The kaolinite, obtained as a fine flour-like powder, was mixed into a smooth paste with distilled water to about 100 per cent. moisture content (by weight). After drying slowly to about 60 per cent. moisture content, the clay paste was gently moulded into a rectangular frame where it was allowed to dry further until it was firm enough to cut into bricks (about 1 in. by $\frac{1}{2}$ in. by $\frac{1}{2}$ in.). The average cross-sectional area was determined from measurements of the breadth and width at three positions using a micrometer.

The pressure-membrane apparatus used were similar in design to those described by Richards (1947). Compressed air was obtained from small gas cylinders which were filled from time to time by a small air compressor. The pressures, which were in the range 10–70 lb./sq. in., were measured by means of ordinary Bourdon type dial gauges. Visking sausage casing was used for the membrane.

The apparatus used for measuring the unconfined compressive strengths of the clay bricks is shown in diagrammatic form in Fig. 5. It is simply a convenient method of applying a vertical load to the sample *S*. It consists of a steel arm *A* pivoted at *B*. The load is applied to the sample through a knife-edge *K* acting in the V-groove cut in a brass disc *D* which rests on the sample (see Fig. 5*b*). This ensures that the load acts vertically. The load is applied by pulling down on a spring balance, attached to the unpivoted end, until the sample fails catastrophically when the spring balance reading is noted. In practice, there is little difficulty in determining this point.

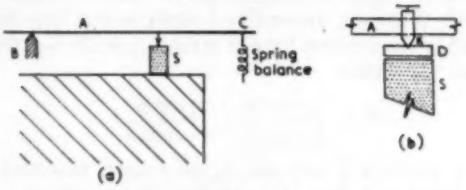

FIG. 5

The load per unit area actually applied to the sample can then be calculated by taking moments about the pivot, and dividing by the cross-sectional area of the clay brick.

The triaxial compression tests

The clay-water mixture was made up as above and preconsolidated in an oedometer under a pressure of 18 lb./sq. in. Three cylindrical samples, 1½ in. in diameter, were removed for testing.

The triaxial compression apparatus used in these tests was an early type manufactured by Leonard Farnell & Co. Ltd. The sample, enclosed in a rubber sheath, sits upon a porous plate through which drainage can occur into a burette. The lateral pressure is applied by means of water fed from a compressed air-water source and measured by a Bourdon type gauge. The loaded plunger acts on a ball-bearing on the sample top plate. The load is applied at a constant rate of strain by a screw jack device operated by an electric motor, suitably geared. A calibrated proving ring and dial gauge between the top of the plunger and the frame of the screw jack device gives the load applied to the sample at any instant, while another dial gauge gives the corresponding vertical compression of the sample.

The clay cylinder was allowed to consolidate fully under the known hydrostatic pressure, the process being followed by collecting the draining water in the burette. Drainage was then completely cut off by closing a stop-cock, and the vertical load applied at a constant rate of strain at 0·15 in./hour. The load and extensiometer dial gauges were read at suitable intervals of time.

The extensiometer readings were expressed as strains (as a percentage of the original length of the sample). The loads, obtained from the calibration curve for the proving ring, were converted into stresses by

dividing by the 'corrected' area of the sample at the corresponding instant. This area was obtained with the aid of the extensiometer readings, assuming that the soil cylinder always remained cylindrical and of the same volume.

The results

The results of the unconfined tests are plotted in Fig. 6, where the vertical axis gives the load at failure per unit area applied to the sample by the spring balance. The suction must be added to this to obtain

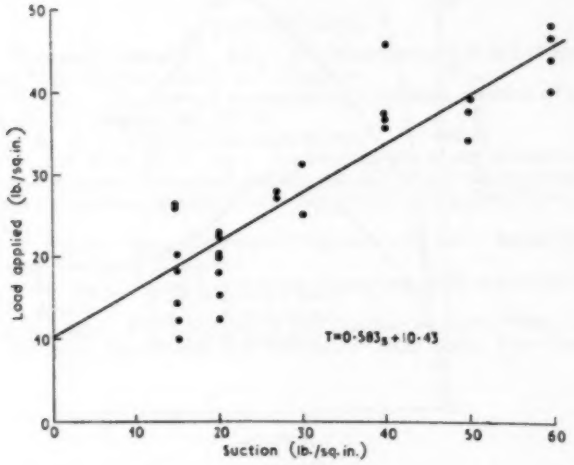

FIG. 6

the total vertical stress σ_1 acting on the sample. Owing to the scatter of points, the Mohr circles were not drawn directly, but the curve in Fig. 6 was determined by the method of least squares and the Coulomb failure line obtained from this by a simple calculation. The Coulomb failure line was found to be

$$F = 0{\cdot}23N + 4{\cdot}2, \tag{7}$$

i.e. angle of shearing resistance $\phi = 13°$,

cohesion $c = 4{\cdot}2$ lb./sq. in.

The stress-strain curves from the triaxial compression tests are shown in Fig. 7 and the resulting Mohr circles are drawn in Fig. 8.

The equation to the Coulomb failure line in Fig. 8 was found to be

$$F = 0{\cdot}23_8 N + 2{\cdot}4, \tag{8}$$

i.e. angle of shearing resistance $\phi = 13°$,

cohesion $c = 2{\cdot}4$ lb./sq. in.

The agreement between the Coulomb failure lines as expressed by equations (7) and (8) give support to the hypothesis that, for a saturated

soil, internal soil-water suction is equivalent quantitatively to an external isotropic pressure.

The above experiments on a saturated shrinking medium having a

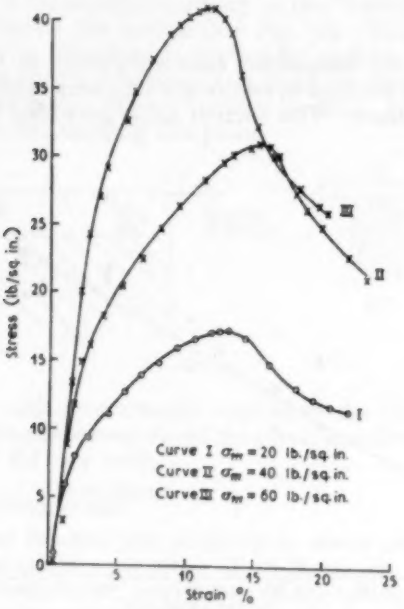

FIG. 7

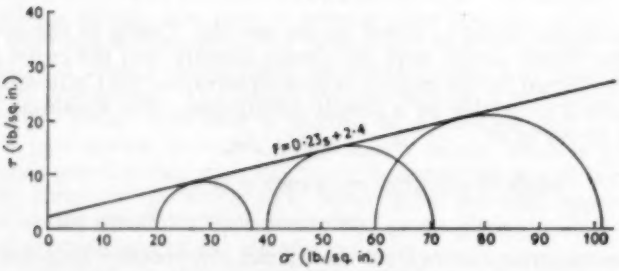

FIG. 8

relatively high air-entry value complement those of Childs (1955) on sand, a rigid inert medium having a low air-entry value. It may be noted that Lewis and Ross (1955) also studied the relationships between shear strength and soil-water suction. They used another technique for measuring shear strength (the vane method) and consequently did not deduce the simple relation described above.

Acknowledgements

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MISCIBLE DISPLACEMENT IN POROUS MATERIALS

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Summary

Miscible displacement has been studied in several porous materials under saturated and unsaturated conditions at different average flow velocities. The tracer appeared at the end of the soil column sooner than would be expected, had no mixing occurred at the boundary of the tracer and tracer-free water. Physical differences between porous materials were manifested by changes in shape and position of break-through curves owing to ionic diffusion. One of the more important physical features was the magnitude of the volume of water not readily displaced at saturation and its increase when the soil was desaturated. Because the total flux of water moving through field soils is generally small, the role played by hydrodynamic dispersion and diffusion in transporting dissolved solutes must be included in the theory of most soil-water processes.

WHEN a fluid containing a tracer in solution is displaced from a porous medium by the same fluid without a tracer, this miscible displacement results in a tracer concentration distribution which depends upon microscopic flow velocities, tracer diffusion rates, and other processes of a chemical nature. Studies of miscible displacement will provide not only a means of determining microscopic flow velocities in soils, but should give a physical explanation of phenomena occurring in leaching of soils, ion exchange and adsorption chromotography, movement of fertilizers, and similar processes.

The flow of water through soil is often considered as bulk movement which can be described by Darcy's law. This description becomes inadequate for the purpose of defining movement of transient dissolved solutes and their chemical processes. It is of interest to measure the ionic or molecular tracer concentration distribution moving through a soil-water system so that the mechanisms of both tracer and water movement may be more clearly understood. The distance a tracer will travel through bulk soil will be determined by the tortuosity of the total path length it follows. Owing to the magnitudes of convection, diffusion, and chemical processes which occur in different pore sequences, the paths of ions of any one type will not be the same and the resulting tracer distribution will clearly give a good deal of information about the behaviour of the water flowing through various soils.

Slichter (1904) attempted to follow groundwater movement through aquifers using salt as a tracer. He observed that a general dispersion or spreading of salt took place from the point of injection which he accounted for by flow velocity distribution in the pores. More recent work involving fluid flow through sands under laboratory conditions (Beran, 1955; Rifai *et al.*, 1956) substantiates the hypothesis of Slichter that the tracer dispersion could be caused completely by flow velocity distribution.

With rare exceptions, all work to date appears to be limited to porous materials completely saturated with fluid and the results are often misleading in their description of dispersion. Inconsistent description of dispersion arises from failure to distinguish between the effects of ionic or molecular diffusion and velocity distribution. Limited experimental techniques have previously been inadequate to ascertain the relative importance of diffusion. In many cases involving miscible displacement experiments, it is tacitly assumed that diffusional effects will be negligible. Working with rather large flow velocities Handy (1959) concluded that ionic diffusion may be disregarded in its effect on tracer distributions within water-saturated sands. In contrast to the above, Berg and Thomas (1959), measuring ion concentrations in column eluates, consider diffusion to be the principal cause of dispersion, thereby entirely neglecting the effects of flow velocity distribution. Their results clearly indicate, however, that the amount of anion adsorption depends upon the chemical and mineralogical characteristics of the soil. It will be shown in this and other reports of this present work that the above results will have to be qualified to include not only the flow velocity distribution but also diffusional effects especially at small average flow velocities.

Day (1956) working with exchange resins has indicated that hydrodynamic dispersion can occur in ion exchange processes without an apparent effect on the dispersion properties of the media. He has also shown that a statistical model proposed by Scheidegger (1954) can be used with some degree of success to calculate the probability of a salt particle appearing some distance from the point of injection in saturated sands. Models proposed by de Josselin de Jong (1958), Rifai (1956), and others have been used to describe dispersion in sands, somewhat less complicated media than common agricultural soils. Although it is not the purpose of the present study, it will be shown in a subsequent paper that existing statistical models used to describe miscible displacement in sands are not suitable for soils or even unsaturated sands. It will further be shown that miscible displacement studies provide a stringent test of the applicability of the similar media concept to soils. The purpose of the present work is to provide basic experimental information regarding the role of hydrodynamic dispersion and tracer diffusion involved in miscible displacement and to discuss their importance to the understanding of soil-water processes.

Experimental

An apparatus was specially designed such that stationary flow conditions and water content of the media could be maintained when tracer-free water was replaced by water containing a dissolved tracer. It was further desired that no mixing of the two waters occurred initially at the boundary between them. At the same time the contribution of flow associated with the boundary between soil and soil container had to be eliminated. Also, samples of effluent to be analysed for tracer concentrations had to be collected without disturbing stationary flow conditions. A cross-sectional sketch of the apparatus is given in Fig. 1. Samples of

air-dry soil screened through a 2-mm. sieve were uniformly packed in the 30-cm. long lucite tube. The water content and the flux density were controlled using hanging water columns and negative air pressure imposed on fritted glass bead porous plates shown on each end of the horizontal column. The use of fritted glass bead plates offers the advantage over other porous materials of having a negligible exchange capacity, large capillary conductivity, and an exceedingly narrow distribution of pores.

The water in the small reservoir behind the inflow plate could be rapidly changed from one containing a tracer to tracer-free water or the reverse by the use of levelling bottles. Burettes graduated to 0·2 ml.

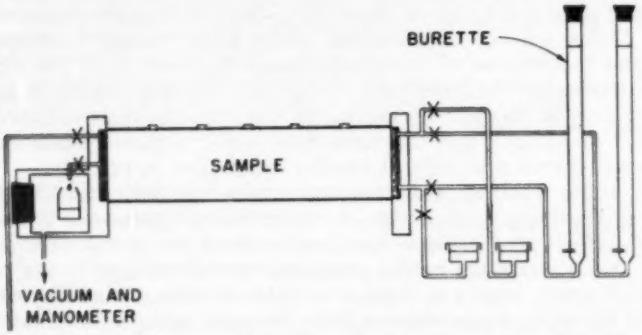

FIG. 1. Schematic cross-section of apparatus used for collecting samples of effluent from soil columns maintained at constant water content and average flow velocity.

were connected in the system to measure the volumes of water which entered the column. The X's in the figure are necessary on-off valves. The vacuum arrangement allowed samples of effluent to be collected as close as possible to the end of the soil column thereby eliminating further dispersion of solutes outside the sample. During the time samples were not being collected, water flow was maintained by means of suction obtained from hanging water columns at the same suction as the vacuum arrangement. The necessary valves for this operation are indicated on the effluent side of the soil column.

The soil-moisture suction over the entire length of column was almost the same even though small differences in suction were required for flow. At the greatest average suctions used, the difference in suctions at the ends of the column never exceeded 5 cm. water. Studies were made under controlled temperature conditions.

Three soils, Oakley sand, Yolo loam, and Columbia silt loam and two sizes of uniform glass beads, 200 μ and 490 μ were used in the investigation. The non-tracer water was boiled water with a concentration of 0·01 N $CaSO_4$. The tracer water was boiled water of 0·1 N $CaCl_2$ concentration. Analysis of the chloride ion was by titration with $AgNO_3$. Problems involving deflocculation and microbial activity were negligible

because a constant volume flux was maintained throughout the entire time of experiments with adjustments in head of less than 0·4 cm. water. The soil columns were flushed free of Cl^- with non-tracer water before each experiment.

Miscible displacements of tracer and tracer-free waters were made using the above-mentioned porous materials at different average flow velocities and different water contents.

Results

All the figures to be presented in this paper have the same general shape and are the result of measuring chloride tracer concentration of effluent from the media. Consider Fig. 2 for Yolo loam in which a 620-ml. slug of water containing chloride tracer of concentration C_0 is

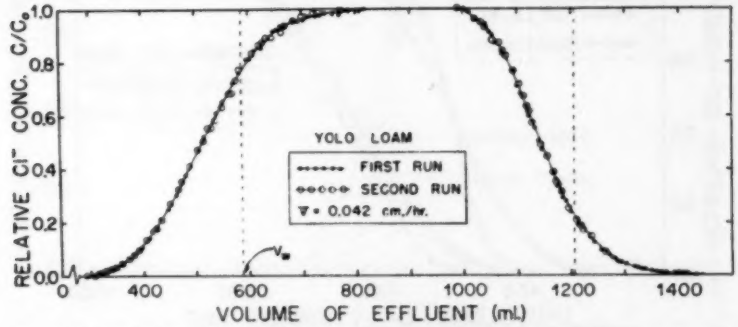

FIG. 2. Relative chloride concentration C/C_0 of effluent from Yolo loam. A 620-ml. slug of chloride tracer water was preceded and followed by tracer-free water in a soil column having a volumetric water capacity v_w of 588 ml.

preceded and is followed by tracer-free water. If piston flow had occurred (i.e. no spreading of the tracer front) the Cl^- distribution or break-through curves would be represented by the broken vertical lines. If no diffusion occurs in a medium having rather large microscopic flow velocities narrow in their distribution, a skewed sigmoid break-through curve will pass through $C/C_0 = 0{\cdot}5$ at v_w (volumetric water capacity of column) and the areas above and below this point will be equal. If the flow velocity is everywhere zero and only diffusion takes place at a tracer front within the medium, a symmetric sigmoid Cl^- distribution curve will pass through $C/C_0 = 0{\cdot}5$ at the original position of the tracer front. The curve in Fig. 2 is skewed and sigmoid but does not pass through $C/C_0 = 0{\cdot}5$ at v_w. The general translation of the experimental break-through curve to the left of $C/C_0 = 0{\cdot}5$ at v_w is not expected after considering the foregoing remarks. This shift is caused by a significant fraction of the total pore volume not contributing to the volume of effluent measured, a fact which will be more fully dealt with later. The reproducible nature of the experimental data for the first and second runs indicates the precision of the method and that soil swelling or

shrinking was negligible during the period of nearly 3 months for which the experiment was continued.

The break-through curve presented in Fig. 3 for Columbia silt loam at an average flow velocity of 0·054 cm./hr. is compared to that of a faster velocity of 2·49 cm./hr. The same soil column was used for both flow velocities. The translation to the left at the smaller flow velocity as well as the slight clockwise rotation is caused by ionic diffusion coupled with hydrodynamic dispersion (attributable to microflow velocity distribution alone) during miscible displacement. In this respect, the break-through curve at the slower flow velocity might be expected to cross the

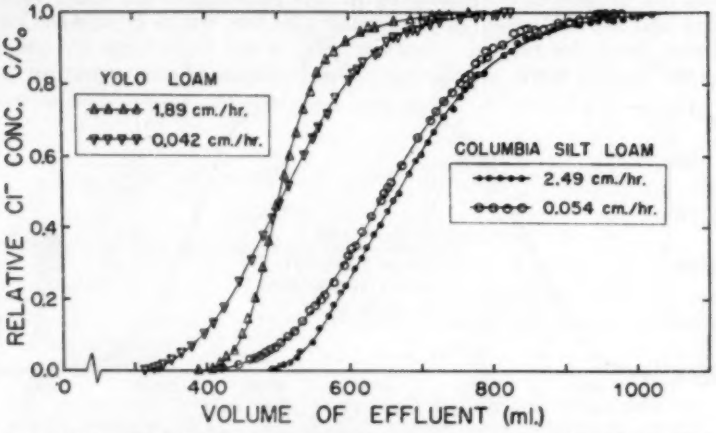

FIG. 3. Pairs of break-through curves using two average flow velocities for Yolo loam and Columbia silt loam. Both soils were water saturated.

break-through curve at the faster flow velocity. However, the flow which occurs in the smaller pores is sufficient to offset this effect. This is not the case for the Yolo loam also presented in Fig. 3. The break-through curves do cross suggesting an important difference between the Yolo and Columbia soils. It is apparent that for the Yolo soil a large number of smaller pores act as static sinks to chloride diffusion. As a result, the diffusion of chloride which occurs from the larger pores having high chloride concentrations into the smaller ones of lower concentration results in a less rapid break-through and a greater transport volume before the maximum $C/C_0 = 1$ is reached. The Columbia on the other hand has a large number of smaller pores actively conducting fluid which tends to mask the effect of diffusion which has occurred.

Data are presented in Fig. 4 to explain the significance of the early arrival of the measured break-through curves compared with that had piston flow occurred. The abscissa in Fig. 4 gives the volume of effluent divided by the volumetric water capacity of a given porous material, i.e. the number of pore volumes displaced. Thus, if one pore volume of tracer water completely displaced the non-tracer water without any mixing at the boundary between the two fluids, the break-through curve

for all materials would be that of the broken vertical line. The displacement of the break-through curve to the left of this vertical line or the area between the two lines is a relative measure of the volume of water not displaced but remaining within the sample. This area has been described previously as 'holdback' (Danckwerts, 1953). The magnitude of the translation would be expected to be associated with soil texture and aggregation, sands having the smallest volume of water not readily displaced and clays the greatest. Fig. 4 shows glass beads and Oakley

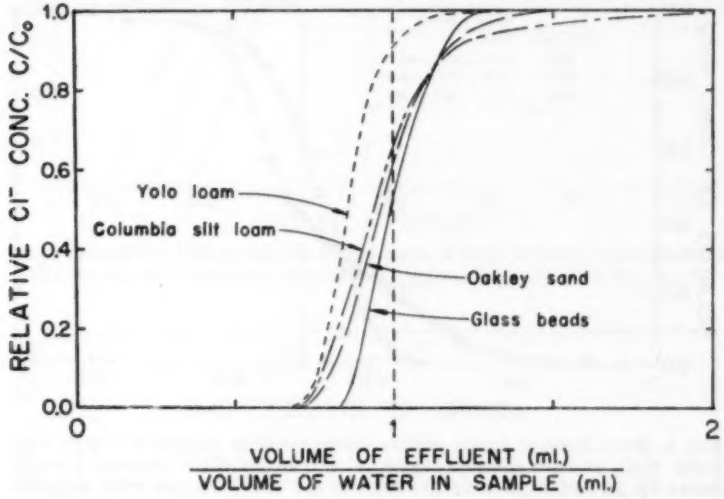

FIG. 4. Break-through curves for four saturated porous materials—Yolo loam, Columbia silt loam, Oakley sand, and glass beads. The average flow velocities were 1·89, 2·49, 0·30, and 1·77 cm./hr., respectively.

sand to have the least holdback while Yolo loam has the greatest. Because of the large flow velocities used for the four materials the effects of ionic diffusion on the translation of the break-through curves are small.

Equations used to describe the process of ion exchange in a medium during passage of a solution containing a tracer subject to exchange must explicitly describe the spreading of tracer owing to hydrodynamic dispersion, diffusion, and exchange. In a subsequent paper of this series now in preparation, data will be presented to show quantitative relations between hydrodynamic dispersion, ionic diffusion, and exchange processes.

It has been shown in Fig. 4 how a break-through curve may be translated to the left because of holdback. On the other hand, curves may be translated to the right for several reasons. The most obvious cause would be that of tracer exchange or precipitation within the soil column. We find that break-through curves will be translated to the right whenever flow takes place at the soil–soil container interface. This flow is not characteristic of that occurring in the bulk sample. Compare the two break-through curves presented in Fig. 5 for the same soil sample

for equal flow velocities and for identical initial chloride concentration in soil and solution. The use of small positive heads of water to control the flow rate yielded curve *A* while the use of small negative heads yielded curve *B*. The negative heads used did not unsaturate the soil column but merely drained about 5 ml. of water associated with the lucite container–soil interface. For positive pressures, the contribution of flow through these filled pores at the soil–soil container boundary results in a curve not representative of the bulk soil. Consideration of

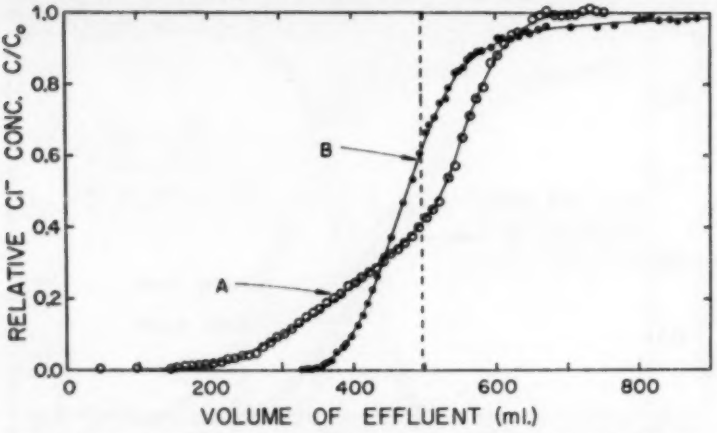

FIG. 5. Break-through curves obtained from the same sample of Oakley sand under slight positive pressure (curve *A*) and under slight negative pressure (curve *B*). In both cases the flow velocities and water contents were identical.

this fact should be given to experiments involving exchange and leaching processes studied in vertical saturated soil columns.

Break-through curves obtained from unsaturated soils yield more information regarding microscopic flow than those from saturated soils. They also provide a more complete description of flow occurring in saturated soils. Fig. 6 shows break-through curves obtained for equal flow velocities from Oakley sand at three water contents. The drier the soil, the greater is the volume of effluent required to reach a maximum $C/C_0 = 1$. Desaturation eliminates larger flow channels and increases the proportion of water which does not readily move within the sample. These almost stagnant water zones act as sinks to ionic diffusion. The relative increase in the volume of stagnant water caused by desaturation is more easily seen in Fig. 7 where relative Cl^- concentration C/C_0 is related to number of pore volumes leached through the column. Desaturating the soil has progressively shifted the curves to the left at the initial break-through which may be explained by an incomplete displacement of one fluid by another. Whereas diffusion is relatively unimportant in saturated sand, it becomes significant at the velocity used under desaturated conditions. This explains the slow approach to $C/C_0 = 1{\cdot}0$ and the increase in skewness of the curves upon desaturation.

Break-through curves were also obtained using columns of glass beads which are relatively inert compared with soils in order that the effects of the ionic charge of the chloride tracer be minimized. The glass beads had diameters of 200 μ and 490 μ and were mixed in proportions of 1 part to 6 on a weight basis, respectively. The two curves shown in

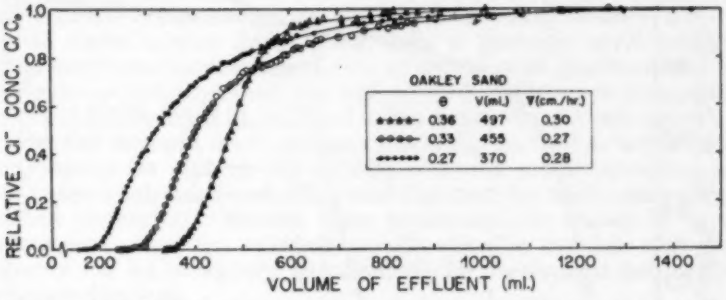

FIG. 6. Break-through curves for Oakley sand at three different water contents. The average flow velocities were of equal order of magnitude at 0·3 cm./hr.

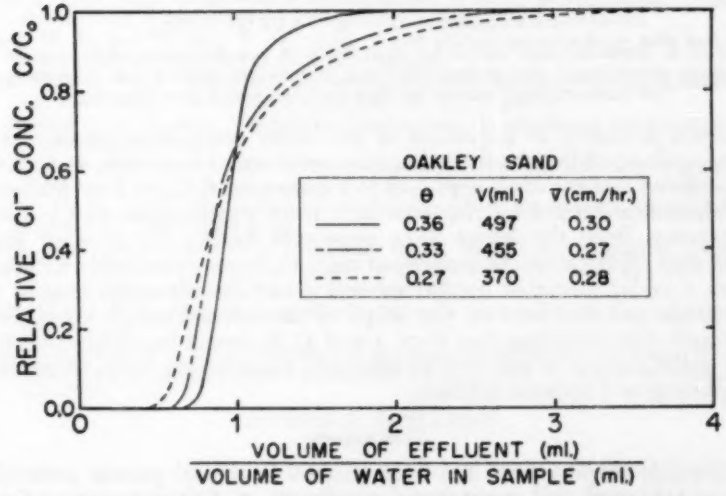

FIG. 7. Same as Fig. 6 except volume of effluent is expressed as pore volumes displaced.

Fig. 8 were obtained from the same sample. Even though the sample of 17·0 per cent. water content had lost half its total water of saturation, the head used to maintain a flow velocity of 1·54 cm./hr. was less than 3 cm. water. There was, therefore, no appreciable difference in water content between the two ends of the horizontal column.

The break-through curves for the glass beads are identical in general

shape to those of the Oakley soil. That is, the magnitude of the holdback increases with decreasing water content and the slow approach to a maximum $C/C_0 = 1$ with the unsaturated sample is similar to that of Oakley. Both the above facts provide further evidence of the incomplete displacement of one fluid by another that occurs in saturated

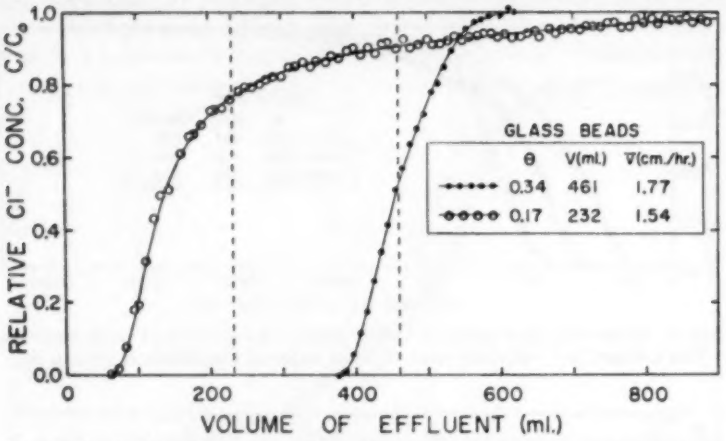

FIG. 8. Break-through curves for glass beads at two different water contents using almost equal average flow velocities. The broken vertical lines represents the break-through curves for each case had piston flow occurred.

samples primarily in sequences of the larger water-filled pores. As a consequence of the above findings in unsaturated materials, it may be considered that the rapid approach to a maximum $C/C_0 = 1$ in saturated conditions is caused by the extremely large contribution of Cl^- concentration from the larger pore sequences having the greatest flow velocities. Even after the concentration C/C_0 is not measurably different from 1 under saturated conditions and if one considers the amount of holdback and its effect on the shape of the break-through curves for different flow velocities (see Figs. 3 and 4), it should be concluded that the soil solution is still not in chemical equilibrium with either the displacing or displaced solution.

Conclusions

Miscible displacement has been studied in several porous materials under saturated and unsaturated conditions at different average flow velocities. The tracer appeared at the end of the soil column sooner than would be expected had no mixing occurred at the boundary of the tracer and tracer-free water. The shapes of the break-through curves for the various media were dependent upon microscopic flow velocity distribution and tracer diffusion.

The shape and position of the break-through curves would also be affected by adsorption and ionic exchange. The flow velocities used in previous experiments were large enough to obscure the mixing by tracer

diffusion. In the present experiment flow velocities were established such that the contribution owing to diffusion was clearly evident. Physical differences between porous materials were manifested by changes in shape and position of break-through curves owing to ionic diffusion. One of the more important physical features was the magnitude of the volume of water not readily displaced at saturation and its proportionate increase when the soil was desaturated. Because the total flux of water moving through field soils is generally small owing to unsaturated conditions coupled with relatively small gradients and low capillary conductivity values, the role played by diffusion in transporting dissolved solutes must be included in the theory of most soil-water processes. For example, most equations describing leaching or ion exchange processes do not separate but actually confound solute movement as a result of hydrodynamic and diffusional dispersion by tacitly using dimensionless parameters. Because these parameters are chosen to fit the experimental data, the equations usually describe the data with great accuracy but fail to account quantitatively for the physical and chemical processes involved.

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